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EMAT SYSTEM FOR ULTRASONIC VELOCITY

Final Technical Report

by

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Abstract

An EMAT system has been designed and constructed which can be used for wall thickness measurements on steel tubes with surface temperatures up to 650°C and for measurements of residual stress near to the inner surface of a 120 mm gun barrel. The system consists of an EMUS (electromagnetic-ultrasonic) transmitter/receiver instrument, a high temperature electromagnetic-acoustic transducer (EMAT) for wall thickness measurements with normally incident shear waves using the pulse-echo-technique and a device consisting of one transmitting EMAT and two receiving EMATs which are collinearly integrated into a mechanical support for the transduction of Rayleigh waves that are travelling along the circumferential direction on the inner surface of a 120 mm gun tube. The residual stress will be evaluated from the time-of-flight of the Rayleigh wave between the two receivers. The EMUS transmitter/receiver provides a tone burst transmitter current signal and r.f. amplification of the received signals. The high temperature EMAT has a water-cooled electromagnet and r.f. coils with the configuration of a twin probe which withstand temperatures up to 250°C. The coils are protected by a thermal shield made from aluminum nitride through which the operating temperature of the r.f. coils is kept below 150°C. The measurement resolution within the specified wall thickness range from 20 to 110 mm is better than ± 0.1 mm. The Rayleigh wave EMATs consist of r.f. coils on comb-shaped ferromagnetic cores, filled with wear-resistant material, in combination with permanent magnets for the bias magnetization. The EMATs are mounted on the mechanical support with a distance of 45 mm between the two receivers. With the Rayleigh wave probe head a relative measurement resolution of 75 ppm is achieved by averaging over 65 shots and a resolution of 25 ppm by averaging over 650 shots.

Keywords: ultrasound, electromagnetic-ultrasonic transduction, ultrasonic velocity, shear wave, Rayleigh wave, wall thickness, residual stress, gun tube

Table of Contents

Page

List of Illustrations

List of Tables

1. Statement of the Problem

The task was to design and to construct an EMAT system which can be used for wall thickness measurements on steel tubes and for measurements of residual stress near to the inner surface of a 120 mm gun barrel. The system shall allow to perform the wall thickness measurements at a surface temperature up to 650°C, whereas the residual stress measurements are to be performed at room temperature. The EMAT system is understood to be an ultrasonic instrument which provides the signals from which wall thickness and residual stress, respectively, can be derived via time-of-flight measurements and subsequent evaluation of the time-of-flight-data using corresponding material data, namely the (temperature-dependent) ultrasonic velocity and acoustoelastic constants, respectively. Provision of the equipment for the time-of-flight measurements and evaluation of wall thickness and residual stress, respectively, from the measured data are not part of the task to be performed under this contract.

Thus the following system components had to be built up:

- a high temperature electromagnetic-acoustic transducer (EMAT) for wall thickness measurements with normally incident shear waves using the pulse-echo-technique

- a device consisting of one transmitting EMAT and two receiving EMATs which are collinearly integrated into a mechanical support for the transduction of Rayleigh waves that are travelling along the circumferential direction on the inner surface of a 120 mm gun barrel

- a transmitter/receiver electronic device for both types of transducers

The wall thickness to be measured ranges from 20 to 110 mm. For the time-of-flight between subsequent backwall echoes a measuring accuracy of about 0.1 µs is required. This value corresponds to a thickness error between 0.1 and 0.2 mm. The probe shall be used in an interval manner with measuring time durations up to 60 s and allowance for sufficient cooling down between two measurement periods.

The ultrasonic system for residual stress measurement shall allow a resolution of approximately 7 MPa (≈ 1,000 psi) for the measured stress and over a spatial distance of about 40 mm in circumferential direction. Calibration of this system will be performed by the customer on tensile specimens of suitable shape.

2. Backgrounds

Ultrasonic wall thickness measurements on hot steel at surface temperatures up to 650°C are difficult to perform with piezoelectric probes and can most conveniently be executed with a transduction technique that does not require any acoustic couplant between the probe and the hot material. Among such techniques electromagnetic-ultrasonic (EMUS) transduction is the most preferable and least expensive alternative. The method is well-developped although careful probe design is necessary in order to achieve a good signal-to-noise ratio and reliable performance under rugged conditions. The design criteria which had to be met for the special task here under question are:

- to acquire sufficient efficiency so that even at the maximum wall thickness of 110 mm with the resultant increase in diffraction and attenuation loss the required measurement accuracy of 0.1 µs is achieved,

- to acquire sufficient axial resolution so that the minimum wall thickness of 20 mm can be measured,

- to compensate for the loss of efficiency produced by the large r.f. coil lift-off which is necessary for thermal and mechanical protection reasons.

High precision time-of-flight measurements with Rayleigh waves are also very conveniently performed with an EMUS system. Its most important properties for this application are especially a good resemblance and reproducibility of signal shapes and the avoidance of any spurious signals which could otherwise be produced by residual couplant. For a probe system to be used inside a 120 mm gun barrel it was required

- to have outer probe dimensions small enough for the space available

- to match the probe surface to the curvature of the inner surface of the gun barrel

- to achieve a signal-to-noise ratio which is sufficient to meet the required measuring resolution

- to mount the probes mechanically in such a way that they are on the one hand rigidly fixed at a constant distance from each other and on the other hand have a controllable and almost constant lift-off during scanning

For both applications an electronic transmitter/receiver system is required that provides sufficient transmitter power and adequately low receiver input noise and which is tunable to the optimal parameters of operation for both applications. The design of such a system had already been developped by the contractor in previous research and development projects so that the task was to build up another of such a system.

3. Approach

Concerning the high temperature EMAT a twin-type configuration of transmitter and receiver coil was chosen for the r.f. coils and an electromagnet with a water-cooled magnetizing coil for the bias magnetization (Fig.1). The Lorentz forces produced in the material by this configuration of bias field and r.f. coil excite normally incident linearly polarized shear waves. Further specific features are:

- the r.f. coil configuration described above produces a smooth sound field without any abrupt phase changes in the far field main beam, so that measurements in the whole wall thickness range from 20 mm to 110 mm can be performed with the same transducer without any difficulties,

- by arranging transmitter and receiver coil side-by-side electromagnetic interference of the transmitter into the receiver and herewith the dead zone are minimized,

- an electromagnet is superior to permanent magnets in producing a large bias magnetization even across an air gap of several millimeters, especially when water-cooling of the energizing coil allows application of a large number of Ampère-turns,

- when the thermal capacities and thermal conductances within the transducer are properly designed, the cooling medium for the magnetizing coil provides also removal of heat from all other transducer parts, so that the probe is much less liable to unforeseen input of heat than an uncooled probe.

The center frequency used and the aperture of the probe had to be optimized in order to achieve a maximum of signal-to-noise ratio and to keep at the same time also for the smallest wall thickness the backwall beyond the near field of the transducer. Materials with sufficient heat resistance had to be chosen for the r.f. coil former, the r.f. coil insulation, the electrical r.f. coil connection and the protective shield in front of the r.f. coils.

For the Rayleigh wave system it was decided to use r.f. coils on comb-shaped ferromagnetic cores, filled with wear-resistant material, in combination with permanent magnets for the bias magnetization (Fig. 2). The probes were to be built into a rigid mechanical support, which should be guided on six adjustable ball rolls through the interior of the gun barrel and equipped with devices for a precise adjusting of the probe lift-off. Such a system provides the following features:

- the EMATs are robust probes with good transduction efficiency and small outer dimensions,

- the probes can easily be matched to the curved surface of the gun barrel by shaping the contour of the ferromagnetic cores,

- in the mechanical construction rigidness and adjustability are combined.

For the wavelength a value of 3 mm was chosen which is on one hand small enough to achieve the necessary axial resolution and on the other hand large enough so that the lift-off effect is as low as possible.

The transmitter/receiver electronics which were assigned to be used in the system consist of a burst generator, tunable between about 0.6 and 1.5 MHz, a 1.5 kW pulse power transmitter amplifier and two receiver channels, each with a low noise preamplifier with 24 dB amplification and a r.f. amplifier with 42 dB amplification and band pass filtering. These electronics can be used for both probe types. Especially, a tone burst signal is the optimal one for excitation of the Rayleigh wave EMATs and yields also a maximum of signal-to-noise ratio of the shear wave normal probe. The loss of axial resolution due to the reduction of bandwidth can be tolerated, since the minimum wall thickness to be measured is 20 mm and the time-of-flight can be measured between corresponding zero crossings of two subsequent back wall echoes.

4. Results

4.1 High temperature EMAT

The first step was to construct a preliminary transducer set-up for trials at room temperature using a laboratory EMUS system. The principal elements of the transducer were similar to that one shown in Fig. 1, but the magnet coil was not water-cooled and therefore energized only for short time durations. The r.f. coils had apertures of $17 \times 7\ mm^2$, and the magnet coil produced approximately 4,500 Ampère-turns. Three different tube segments with an inner radius of 60 mm and 20 mm, 65 mm and 110 mm wall thickness, respectively, made from St37 steel grade were used for the experiments. The gap between the r.f. coils and the material was 1.7 mm. A VELONEX High Power Pulse and Burst Generator Model 570 was used to feed the r.f. current tone burst (22 A_{p-p}) into the transmitter coil. The transmitter current generator was externally driven by a burst signal with a center frequency of 1.08 MHz of 4 cycles duration. Transmitter and receiver coil were tuned to series and parallel resonance, respectively. Preamplifier and r.f. amplifier in the receiver channel were similar to those used later in the EMUS transmitter/receiver instrument.

Fig. 3 shows the signals obtained with this set-up on each of the three specimens mentioned. The signal-to-noise ratio of the first backwall echo is 27 dB at 110 mm wall thickness and 34 dB at 65 mm wall thickness. At 20 mm wall thickness the third backwall echo is the first one, that is not affected by the dead zone, and has a signal-to-noise ratio of 35 dB. The axial resolution is sufficient to resolve the minimum wall thickness, which is 20 mm. Another trial of this kind with r.f. coil apertures of $14 \times 6\ mm^2$ yielded signal-to-noise ratios that were about 6 dB lower. Therefore preference was given to the configuration with the larger aperture. The near field length is in this case approximately equal to the smallest wall thickness that has to be measured. An increase of the frequency is not necessary and would result in a decrease of the signal-to-noise ratio.

The high temperature shear wave EMAT was constructed on the basis of these results according to the scheme of Fig. 1. Photographs of the EMAT are shown in Fig. 4. The water-cooled magnet coil produces 7,500 Ampère-turns at a d.c. current of 20 A. A cooling water flow of 10 l/ min is required for operation at room temperature as well as at increased temperatures. The external yoke legs are matched to the curvature of a tube with 340 mm outer diameter. The coil former is made from glass fiber-reinforced polyimide which withstands a continuous operating temperature of 250°C. The insulation of the wire of the r.f. coils has a specified lifetime of 20,000 h at 240°C. For the electrical connections in the interior of the probe a coaxial cable is used that withstands a continuous operating temperature of 260°C. The solder used for the r.f. coils has a liquidus point of 309°C. The protective shield in front of the r.f. coils is a disk from aluminum nitride with a thickness of 0.635 mm. Owing to the large thermal conductivity of this material there is efficient heat transfer from the thermal shield to the cooling chamber containing the magnet coil.

Figs. 5 to 7 illustrate the performance of this probe on the three specimens already mentioned in connection with the EMUS transmitter/receiver instrument G4401 described below. The magnetizing current for the bias magnetization is provided from a Hewlett Packard DC Power Supply 6268B. The transmitter current is a tone burst signal with a center frequency of 1.07 MHz, a duration of 4 cycles, and an amplitude of approximately 28 A_{p-p}. The length of the cables between the transmitter/receiver instrument and the probe is about 10 m. The gap between the r.f. coils and the material surface is 3.0 mm. At dual trace operation the oscilloscope screen photographs show the backwall echo sequence on the upper trace and the transmitter current signal on the lower trace. The first backwall echo has a signal-to-noise ratio of 39 dB at 65 mm wall thickness and 33 dB at 110 mm wall thickness, at 20 mm wall thickness the third backwall echo has a signal-to-noise ratio of 39 dB. At 110 mm wall thickness the signal-to-noise ratio of the second backwall echo is 25 dB. The resemblance of two different backwall echoes is extremely good, in particular there is no ambiguity in the identification of corresponding zero crossings. So evidently a way to measure precisely the time-of-flight between subsequent backwall echoes is to use the corresponding zero crossings. The repetition frequency is about 130Hz, this is sufficient for signal averaging over many shots in a short time interval, if further improvement of the signal-to-noise ratio is necessary.

The influence of lift-off on signal amplitude and apparent time-of-flight shift of the first backwall echo is depicted in Fig. 8. In this figure the change in time-of-flight refers to the time measured between the transmitter current signal and the first backwall echo. A lift-off variation of 1.5 mm changes the apparent time-of-flight between these signals by 40 ns, which corresponds to a thickness error of not more than 0.06 mm, whereas the time-of-flight measured between two subsequent backwall echoes is not at all affected by the variation of lift-off. The influence of lift-off variation on the echo amplitude amounts to about 4 dB/mm, which is a rather small value.

The typical scatter of the time-of-flight data is about ± 13 ns for single shot measurements and about ± 2 ns for averaging over approximately 65 shots, as can be seen from Fig. 9. This scatter is far within the required measurement resolution.

To evaluate the wall thickness from the time-of-flight with the shear wave velocity known one has to consider the specific sound paths of the backwall echoes that are produced by a twin probe (Fig. 10). One derives from this figure that the time-of-flight Δt_{nm} between the mth and the nth backwall echo is

$$\Delta t_{nm} = \frac{2n\left\{\left[\frac{a}{2n}\right]^2 + d^2\right\}^{1/2} - 2m\left\{\left[\frac{a}{2m}\right]^2 + d^2\right\}^{1/2}}{v_t} \qquad (1)$$

where d is the wall thickness, v_t the shear wave velocity and a the center-to-center distance of transmitter and receiver coil.

The accuracy of the ultrasonic wall thickness measurements has been checked on the three tube segments mentioned above by a comparison to mechanical measurements (Tab. 1). For each specimen the time-of-flight has been calculated from the wall thickness and the shear wave velocity. The latter has been determined from the measurement at 110.1 mm wall thickness. The absolute error is in all cases less than 0.05 mm, i.e. the required accuracy is fully achieved.

Tab. 1: Comparison of ultrasonic and mechanical wall thickness measurements

wall thickness [mm]	backwall echos	time-of-flight [μs]		relative error [%]
		calculated[1]	measured	
20.35	3rd/4th	12.556	12.532	-0.19
65.0	1st/2nd	40.127	40.135	+0.02
110.1	1st/2nd	68.006	68.003	-

[1]according to Eq. (1) using v_t = 3.237 m/s, a = 7.5 mm

The performance of the probe at increased temperatures was tested on a specimen from St37-2 steel grade (carbon content ≤ 0.20%) with dimensions of approximately 200x100x45 mm^3. The specimen was heated in a furnace to a temperature of 850 to 900°C, then taken out of the furnace and put on a fire-brick, which had been heated together with the specimen. Another fire-brick was used to achieve sufficient thermal isolation. This procedure allowed to perform measurements at a specimen surface temperature of about 600 to 650°C for some minutes. The surface temperature of the specimen was measured by means of a thermocouple. Initially the temperature change of the r.f. coils was observed by measuring the change of the d.c. resistance during a heating and cooling cycle putting at first the probe on the hot specimen and then allowing it to cool down in air. The result is given in Fig. 11. Obviously the temperature saturates at an equilibrium value after

2 to 2.5 min and would even in continuous operation remain far below the limit which is given by the heat resistance of the materials used for the r.f. coils and the electrical connections. The time constant of the heat transfer to the probe is approximately 30 s.

Examples for the excitation of ultrasound with this probe in the temperature range between room temperature and 650°C surface temperature are given in Fig. 12. The oscilloscope screen photographs show the backwall echo sequence on the upper trace and the transmitter current signal at a sensitivity of 10A/V on the lower trace. The increase of the time-of-flight between subsequent backwall echoes with increasing temperature illustrates the temperature dependence of the ultrasonic velocity. The ratio between backwall echo amplitude and transmitter current amplitude is a measure of the transducer efficiency, and the variation of the ratio of first and second backwall echo amplitude gives an estimate how the ultrasonic attenuation varies with temperature. These data have been evaluated from measurements at different temperatures and are plotted in a diagram in Fig. 13.

Obviously the efficiency at 650°C surface temperature is nearly the same as at room temperature and has a broad maximum at temperatures between 400 and 550°C. The reason for the increase of efficiency in this temperature range is in some doubt. It may either be due to the efficient EMUS transduction of ultrasound in the scale that is formed on the surface during cooling from 800°C to lower temperatures or may be an inherent property of the St37-2 steel grade and related to a retarded phase transformation from γ-iron to perlite. Experiments in an oxygen-free atmosphere during which the formation of scale could be eliminated were beyond the scope of this contract. Nevertheless the conclusion can be drawn that the transducer efficiency is up to surface temperatures of 650°C at most lowered by 3 dB in comparison to room temperature.

The variation of the ratio between first and second backwall echo amplitude with temperature is rather small. Therefore the changes of ultrasonic attenuation cannot be evaluated very precisely, and the related curve shown in the diagram may [illegible] of significance. The essential result is that the increase of ultrasonic attenuation with temperature does not exceed 15 dB/m in the temperature range between room temperature and 650°C. Therefore it is expected that the decrease of the signal-to-noise ratio of the second backwall echo due to an increase of ultrasonic attenuation is at 110 mm wall thickness not larger than 6 or 7 dB. The signal-to-noise ratio measured at room temperature for a single shot is 25 dB (see above), so it will not be lower than 15 dB at 650°C surface temperature. The loss of 10 dB may even be compensated by averaging over 10 shots.

Fig. 14 shows an example for the result of an automated measurement of the time-of-flight between first and second backwall echo on the heated specimen with approximately 45 mm thickness. The decrease of the time-of-flight plotted versus time corresponds to the increase of ultrasonic velocity during the cooling down of the specimen. The surface temperature was approximately 620°C in the beginning and 530°C at the end of the measurement. The interrupts in the plot occurred, because the large increase of the signal amplitude during the measurement (see Fig. 13) had to be compensated by an adjustment of the amplification in the specific time-of-flight measuring equipment used for this experiment.

The times-of-flight measured between subsequent backwall echoes at different temperatures were evaluated in order to obtain the shear wave velocity as a function of the surface temperature. These data are plotted in Fig. 15. They are rather consistent with other data available from literature [1] if the reasonable assumption is made that a surface temperature of 650°C corresponds to a mean temperature of about 700°C across the thickness of the specimen.

With these results the construction of the high temperature shear wave EMAT was successfully completed.

4.2 Rayleigh wave probe head

The customer had supplied a ring section from a 120 mm gun tube with a width of 45 mm. This specimen was used for trials employing the laboratory EMUS system described above and three Rayleigh wave EMATs having the structure illustrated in Fig. 2. The ferromagnetic cores of the EMATs were 17 mm long, 12 mm wide, and 6 mm high. The radius of curvature of the outer contour of the cores was 60 mm and thus matched to the curvature of the gun tube. The comb structure consisted of 7 teeth. The permanent magnets were from neodyme-iron-boron and had dimensions of $20 \times 18.6 \times 5.5$ mm^3. Small iron blocks with dimensions of $20 \times 18.6 \times 8$ mm^3 on top of the permanent magnets were used to get the optimal bias magnetization value. A foil of 135 µm thickness was used to produce a corresponding gap between the transducers and the material. The transducers were positioned collinearly on the inner surface of the specimen along the circumferential direction. Into the transmitter coil was fed an r.f. current tone burst with a center frequency of 0.93 MHz, a duration of 5 cycles and an amplitude of 15 A_{p-p}. Transmitter and receiver coils were tuned to series and parallel resonance, respectively.

Fig. 16 shows the signals obtained with this set-up. The signal-to-noise ratios are 32 to 34 dB. The center-to-center distance between receiver 1 and receiver 2 of approximately 45 mm is sufficiently large so that the two signals do not overlap. Obviously the transducer length is as long as possible in order to get a sufficient signal-to-noise ratio and as short as necessary in order to achieve the required axial resolution. It was concluded that a value of 45 mm was a good compromise for the center-to-center distance of the two receivers. This distance corresponds to an angle of 43° between the radial vectors to the center of the two receivers. A value of 57° was chosen for the equivalent angle corresponding to the distance between transmitter and receiver 1.

Once these results had been achieved the mechanical support for the probes was designed and built up. The Figs. 17 and 18 show photographs of the probe head after completion. The transducers are built into individual brass housings and protected by a wear-resistant filling material. The ball rolls on the two ring sections can be adjusted to the actual inner diamter of the gun tube. The brass housings of the transducers are rigidly guided by a key and slot-construction. The gap between the transducers and the inner tube surface can be optimized through variation of the position of brass wedges one of which is visible in the lower photograph of Fig. 17. The wedges are moved along thread rods, the screw heads of which are visible on the lower photograph of Fig. 18. The two preamplifiers are mounted on an adapter which may be used to connect the probe head mechanically to a steering device.

Figs. 19 and 20 illustrate the signals that are obtained with this probe head in connection with the EMUS transmitter/receiver instrument G4401 from the 120 mm gun tube ring section. The cables to the probe head have a length of 10 m. The other measurement parameters are similar to those referring to Fig. 16. The signal-to-noise ratios are 34 to 36 dB (The electrical noise in the second receiver channel appears to be somewhat larger than in the first one since the amplification in the two channels differs by about 2 dB). It is also shown that the signals in the two receiver channels may be added without any overlap occuring between the transmitted pulses. The degree of resemblance between the pulses from receiver 1 and receiver 2 is extremely high, so that corresponding zero crossings are unambiguously identified.

The measurement resolution that is obtained from these signals is illustrated in Fig. 21. With averaging over 65 shots the scatter is about $\pm$ 1.2 ns, with averaging over 650 shots it is reduced to approximately $\pm$ 0.4 ns. This scatter corresponds to a relative resolution of 75 and 25 ppm, respectively. The lower diagram in Fig. 21 shows that in the measuring time interval of roughly 20 min the time-of-flight increases by about 1.5 ns. This is obviously due to an increase of temperature. A corresponding decrease of the Rayleigh wave velocity is produced by a temperature change of 1°C.

There was no part of a gun tube available that was sufficiently long to perform a scanning experiment. Therefore some seamless drawn steel tube with an inner diameter of 120 mm and 5 mm wall thickness was used for this kind of experiment. The probe head was scanned in circumferential direction and the time-of-flight of the Rayleigh wave between receiver 1 and receiver 2 was measured in an automated manner (actually the probe head was held by hand and the tube was turned at a constant velocity using a bogie). As Fig. 22 shows, the tube unfortunately has a significant and inhomogeneous crystallographic texture which results in large variations of the Rayleigh wave velocity along the circumference of the tube. Therefore an intimate check of measurement resolution during scanning was not possible. Nevertheless as far as the reproducibility of the data can be demonstrated on this specimen it is rather good as can be seen from a comparison of the measurement result for different revolutions.

4.3 EMUS transmitter/receiver instrument

The EMUS transmitter/receiver was built up as described above. Photographs of the instrument are shown in Fig. 23. Its performance has already been illustrated by the results given in paragraph 4.1 and 4.2. The instrument is specified as follows:

- burst generator tunable from 0.6 to 1.5 MHz

- transmitter current tone burst signal: length from 1 to 10 cycles, amplitude up to 30 A_{p-p}

- transmitter tuning capacitance from 0.2 to 3.0 nF

- preamplifier: input noise 20 $nV_{p-p}/(Hz)^{1/2}$ between 500 kHz and 5 MHz with input terminated by 50 Ω, gain 24 dB

- r.f. amplifier: 2 channels, gain 42 dB each, passband from 0.50 to 1.6 MHz

5. Discussion

The tests of the high temperature shear wave EMAT have shown that the second backwall echo attains at room temperature at the specified maximum wall thickness of 110 mm a signal-to-noise ratio of 25 dB, and at a surface temperature of 650°C a signal-to-noise ratio of not less than 15 dB. By automated time-of-flight measurements using corresponding zero crossings of subsequent backwall echoes it has further been verified that for a signal-to-noise ratio of 22 dB the measurement resolution is at single-shot evaluation within ± 13 ns, which corresponds to a thickness error of not more than ± 0.02 mm. On the other hand even at the specified minimum wall thickness of 20 mm two subsequent backwall echoes are completely resolved. These results show that the specified measurement accuracy is fully achieved. Cable lengths up to 10 m between probe and transmitter/receiver electronics are allowable, which enables and facilitates operation of the equipment under the conditions of the required task. The lift-off variation of the echo amplitude of only 4 dB/mm is so moderate, that no problems with varying lift-off will arise. An effect of lift-off upon the time-of-flight measured between two backwall echoes was ruled out by the experiments. Care was taken in the design of the probe that a large r.f. coil lift-off would be tolerated, so that thermal protection could be manifested by a ceramic shield, which for his part has sufficient lift-off from the material surface to be safe from mechanical damage. The materials chosen for the r.f.

coil and the electrical connections allow an operating temperature of these parts up to 240°C, whereas on the other hand owing to the large thermal conductivity of the thermal shield these temperatures can be kept under the specified conditions below 150°C. This provides a large safety margin against thermal damage.

The Rayleigh wave probe head has well been integrated into the space available in the interior of a 120 mm gun tube. Signal-to-noise ratios of typically 35 dB have been achieved. It has been verified that by averaging over approximately 65 shots a measurement resolution of ± 1.2 ns will be achieved. For a relative velocity change of 7 ppm at 1,000 psi (a typical value for the acoustoelastic effect on the Rayleigh wave [2]) and the given distance of 45 mm between the two receivers this corresponds to a measurement resolution of 10,500 psi. Averaging over 650 shots improves the measurement resolution to even ± 0.4 ns corresponding to a resolution of 3,600 psi. On the other hand this measurement resolution can only be obtained, if the distance between the two receivers is constant within ± 1 µm. Therefore care has been taken that the receivers are as rigidly as possible held in their positions. At the same time the device had to allow for an adjustment of the lift-off of each individual probe. This requirement was fulfilled by an appropriate mechanical construction. Furthermore the temperature dependence of the ultrasonic velocity and the thermal expansion produce a change of the time-of-flight of approximately 100 ppm/°C and thus can disturb the measurements whereby the influence of temperature on the ultrasonic velocity is dominating. Therefore good thermal stabilization is necessary when precise measurements are required. When measurements at different temperatures are compared to each other the influence of temperature has to be taken into account.

The EMUS transmitter/receiver instrument is part of the equipment that is required to obtain the results discussed so far. The tuning range of the burst generator is fully sufficient to cover the range from 0.90 to 1.10 MHz which is used for the two applications.

6. Conclusions and Recommendations

The EMAT system for ultrasonic velocity has been built up and the objectives of the project have been achieved. To measure the time-of-flight between two ultrasonic signals it is recommended to use corresponding zero crossings of these signals. A maximum of measurement accuracy can be achieved by averaging over up to 1,000 shots. In order to obtain a measurement resolution of $\pm$ 0.4 ns with the Rayleigh wave probe head the distance between the two receiver probes has to be kept constant within $\pm$ 1 µm and the system has to be thermally stabilized within $\pm$ 0.25°C.

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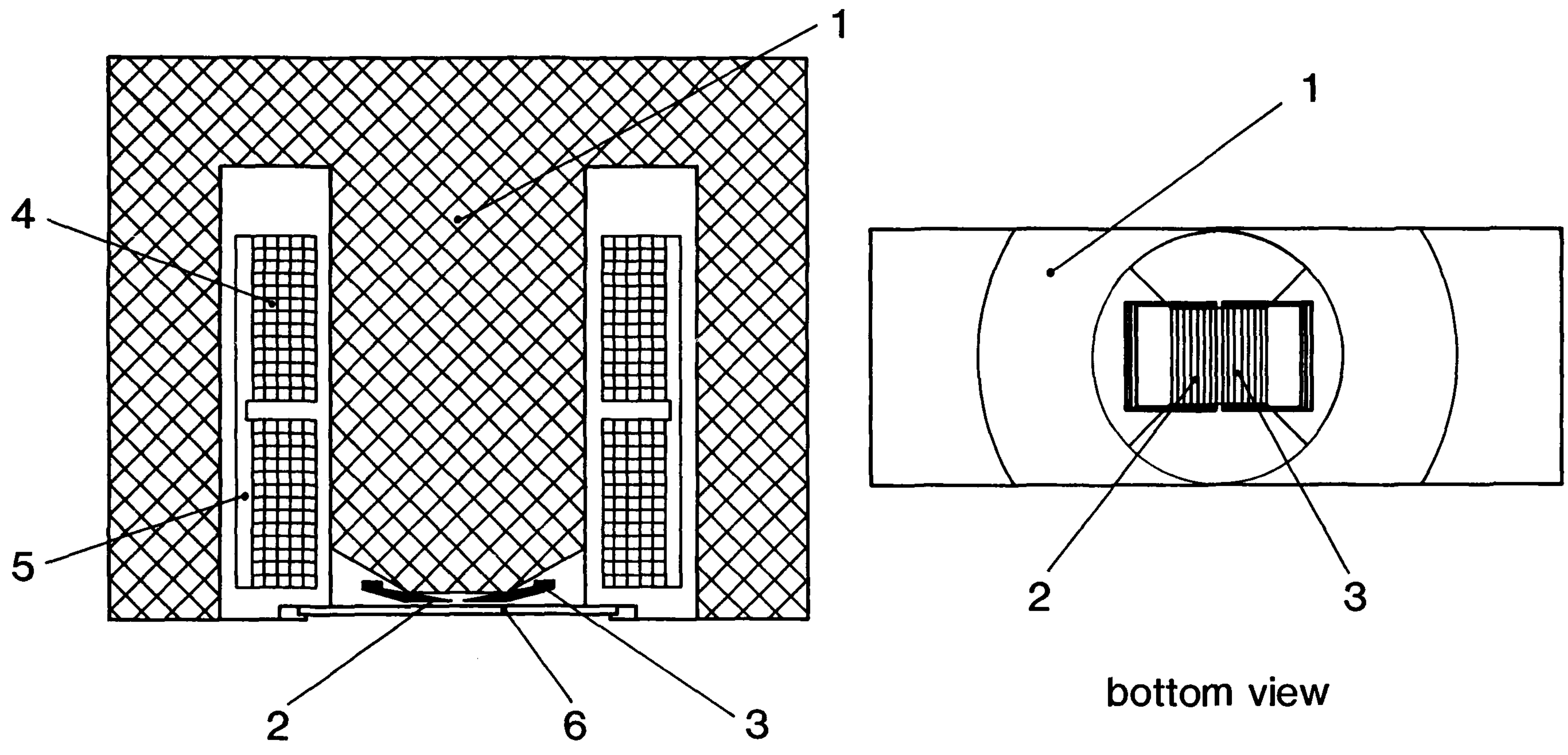
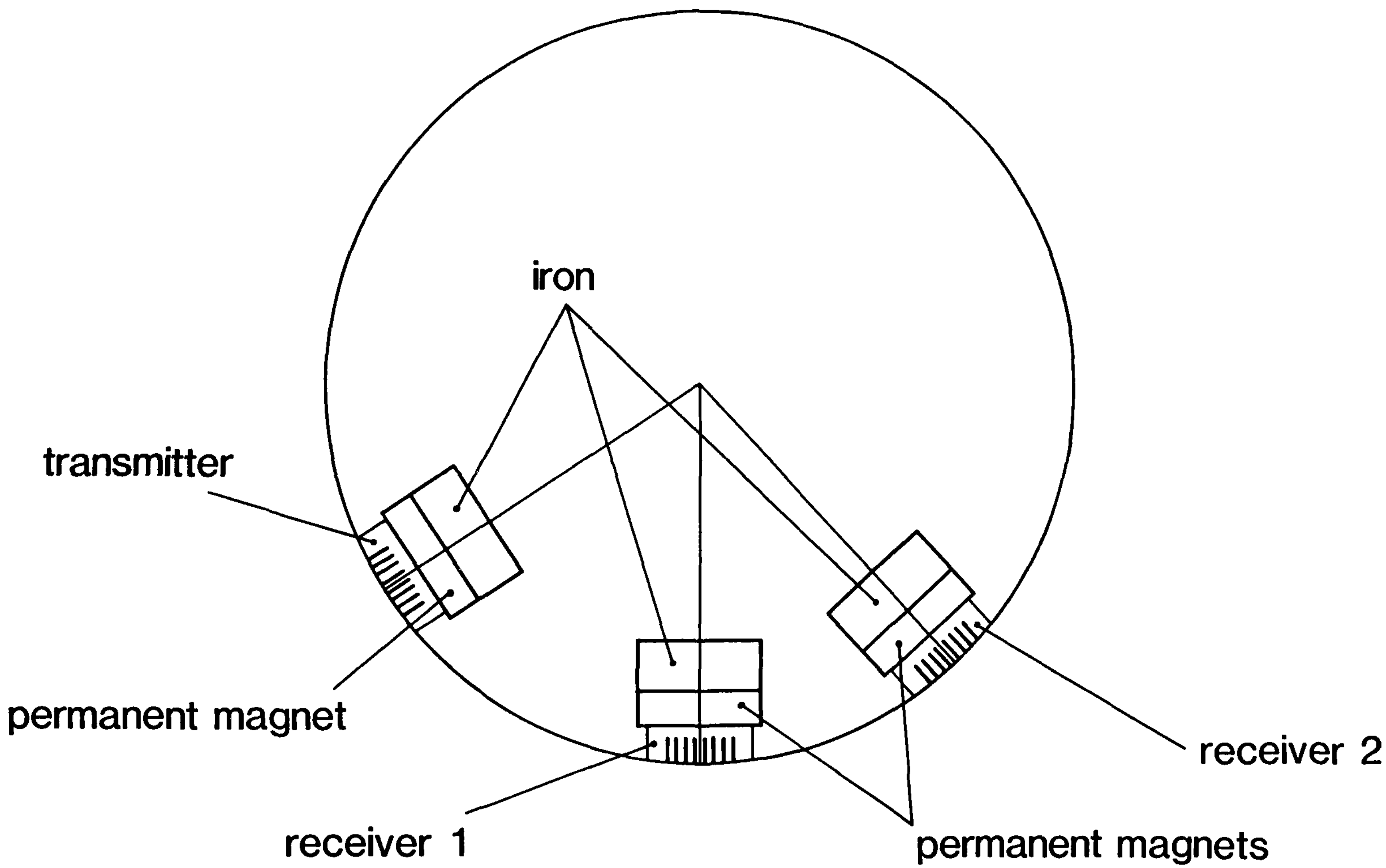


1 magnet yoke
2 transmitter coil
3 receiver coil
4 magnet coil
5 cooling chamber
6 protective shield

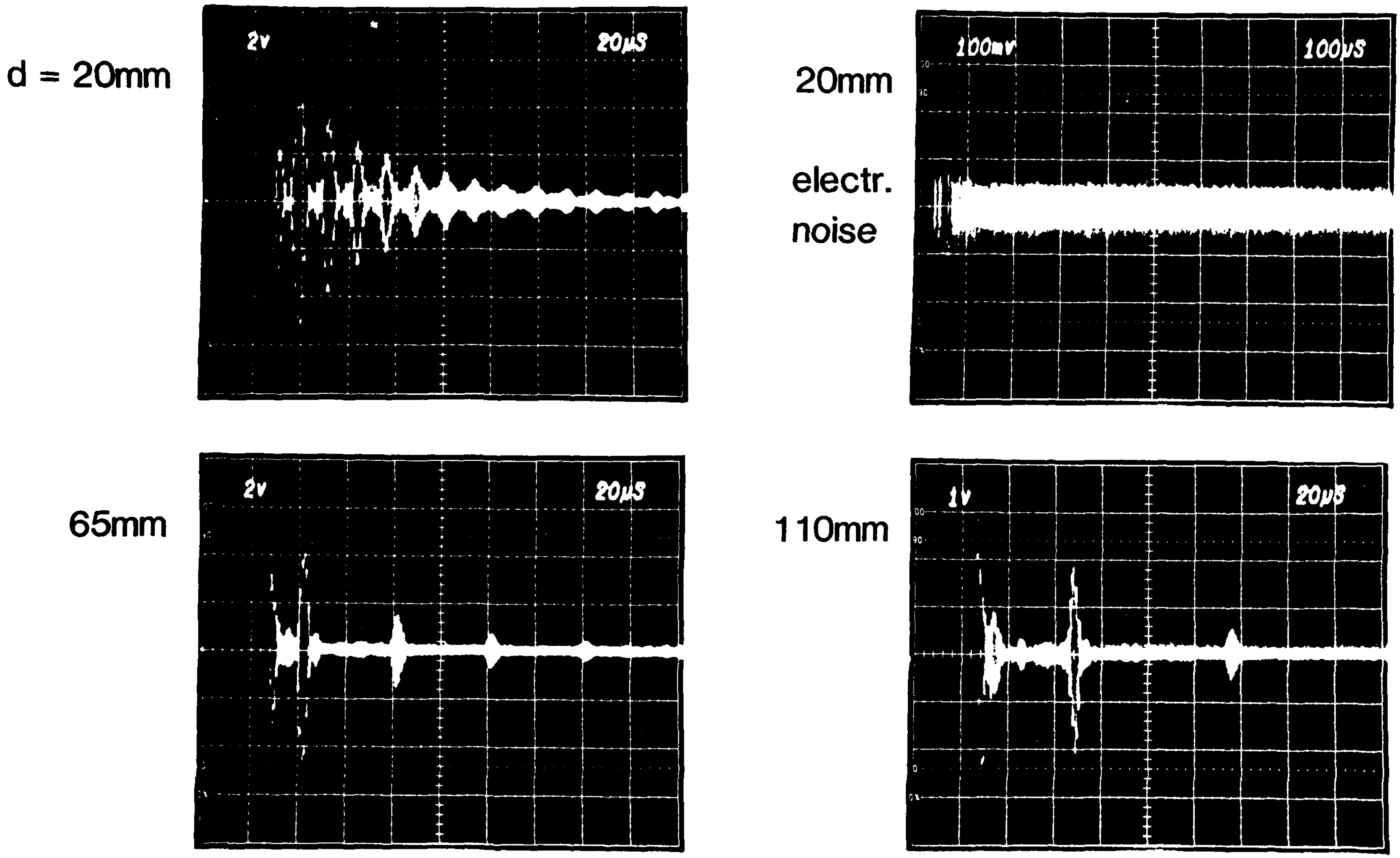
IzfP | Construction of the shear wave normal probe (schematically) | Fig. 1



IzfP

Arrangement of the EMATs for the Rayleigh wave system

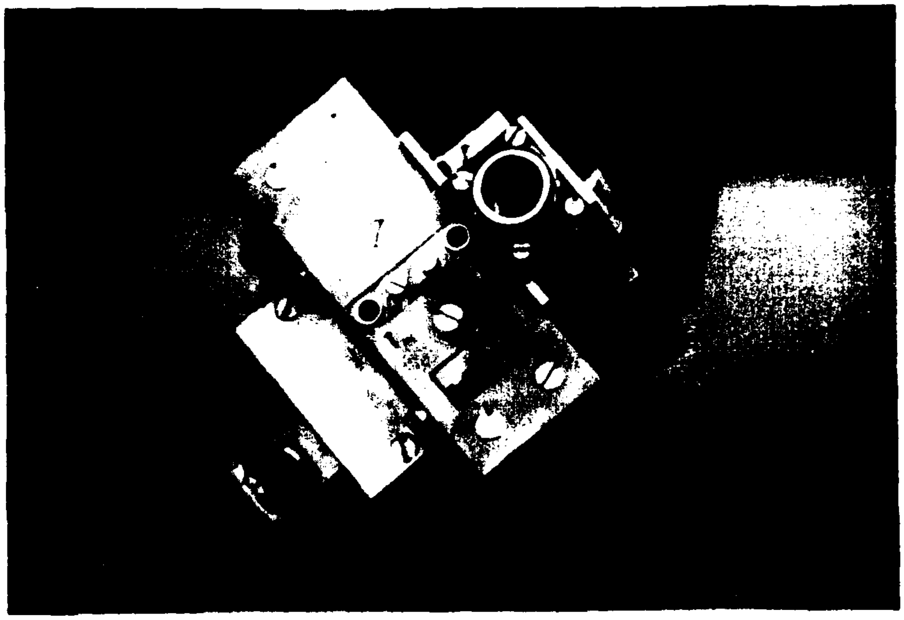
Fig. 2

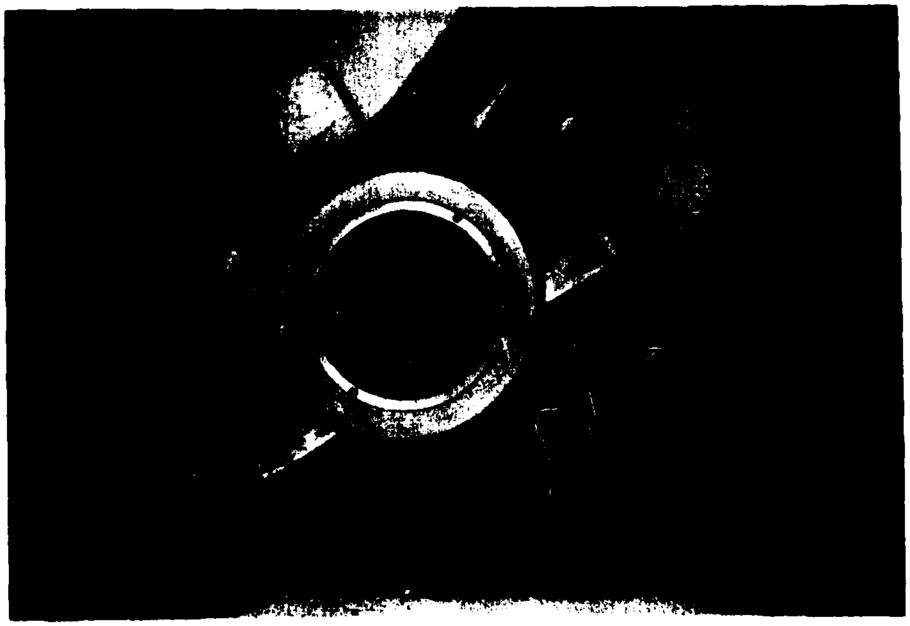


IzfP

Laboratory EMUS system: Backwall echoes from tube segments with different wall thickness d

Fig. 3

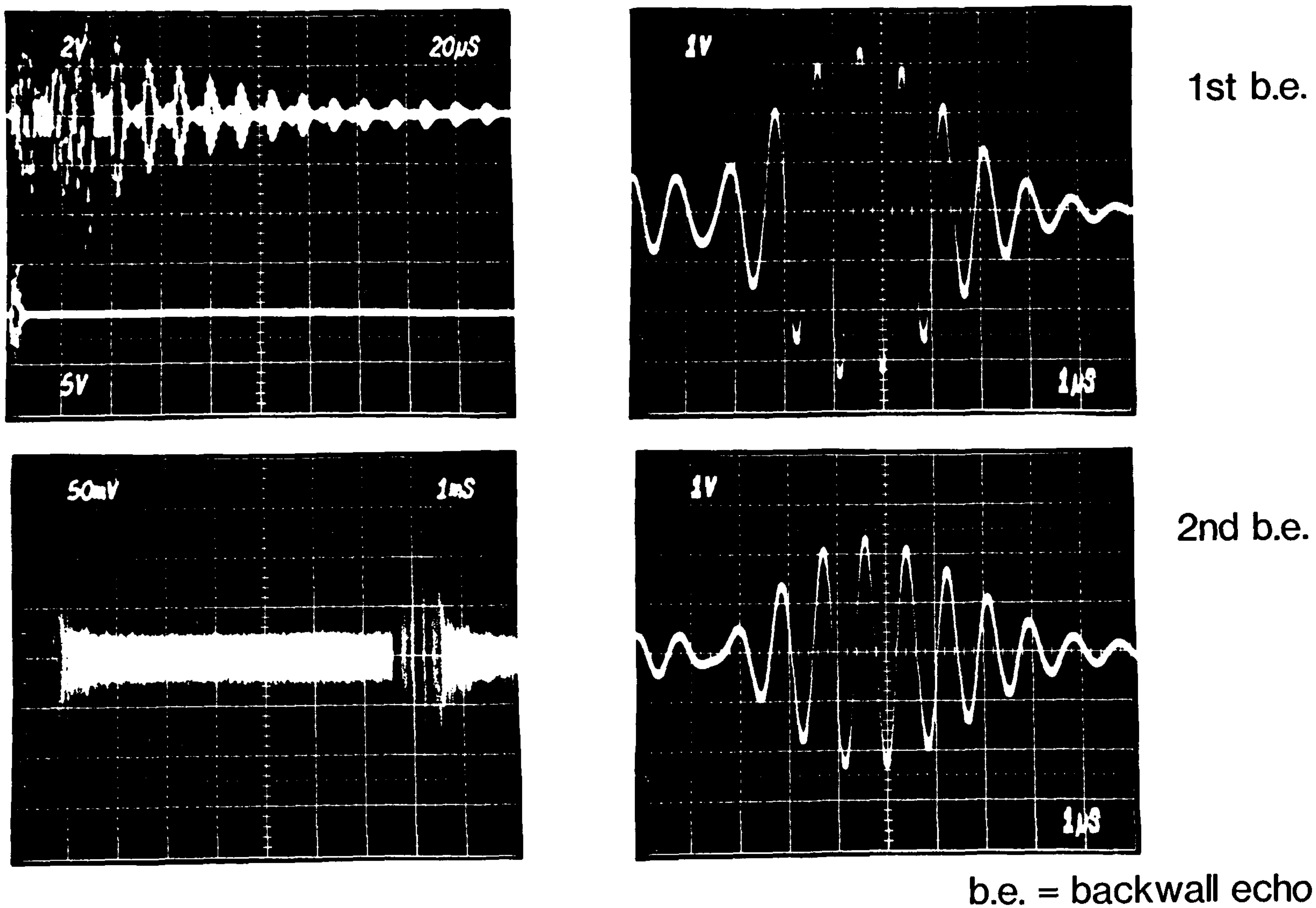




High temperature normal shear wave EMAT

IzfP

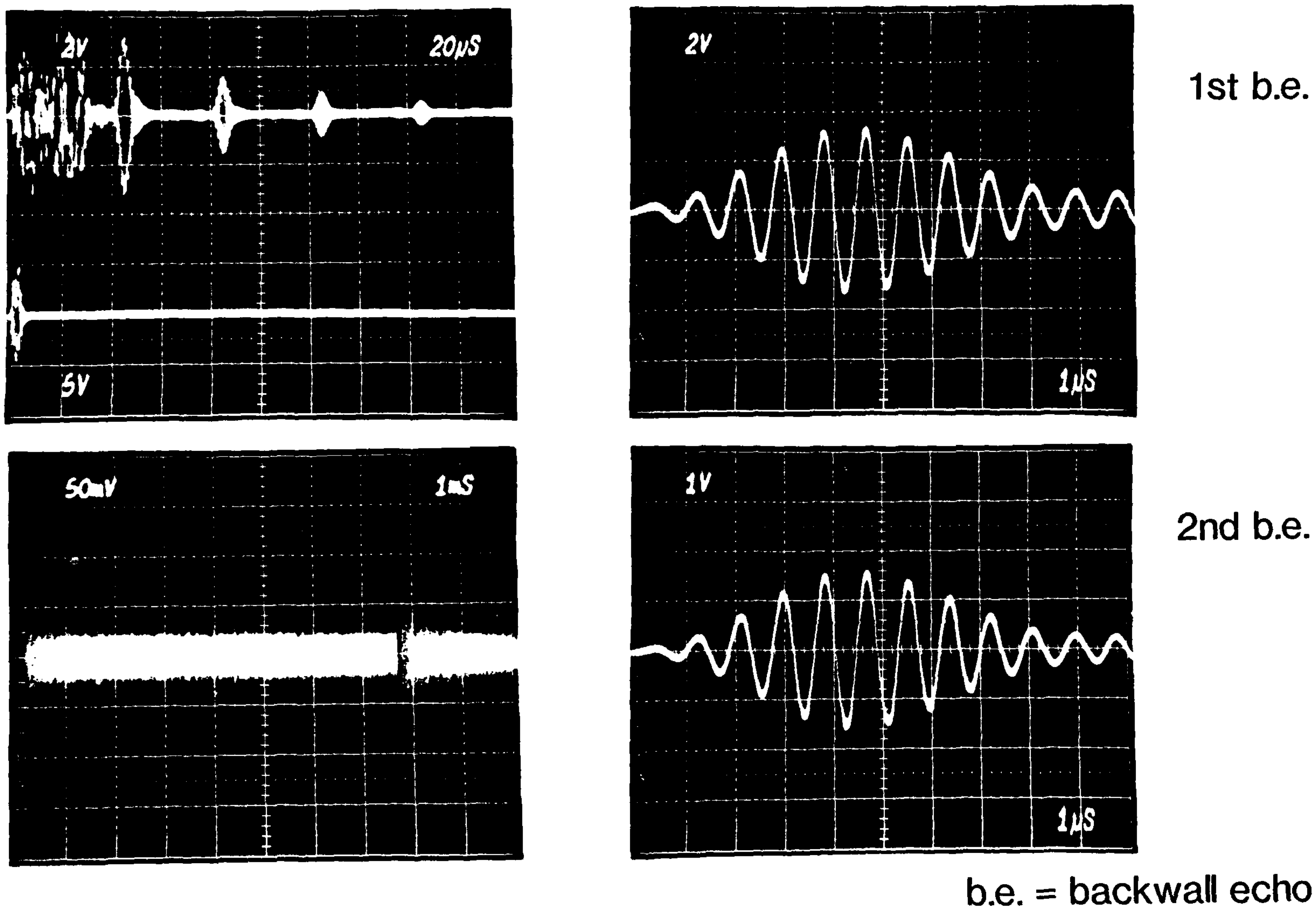
Fig. 4



IzfP

High temperature normal shear wave EMAT on tube segment
(d = 20mm , RT)

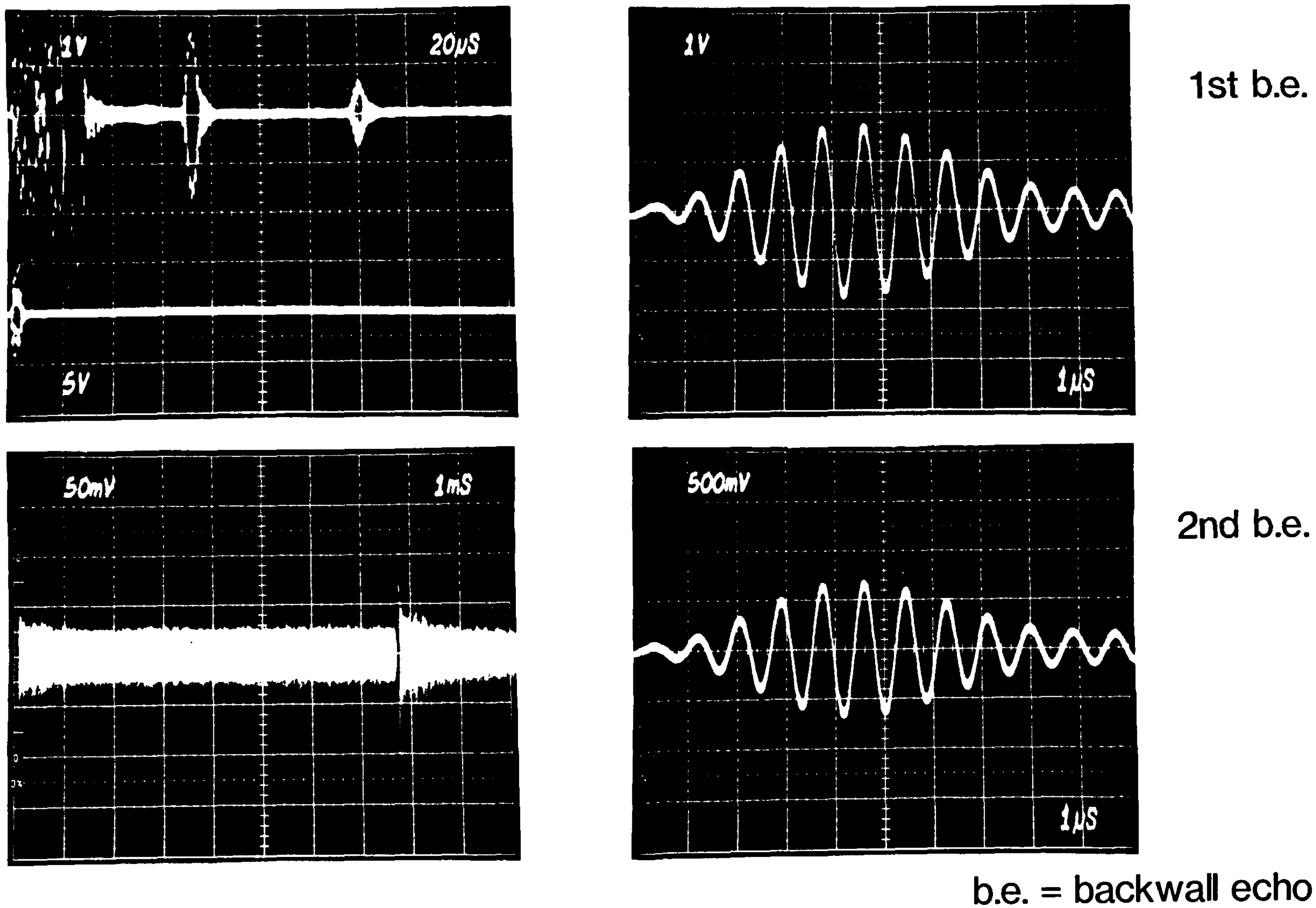
Fig. 5



IzfP

High temperature normal shear wave EMAT on tube segment
(d = 65mm , RT)

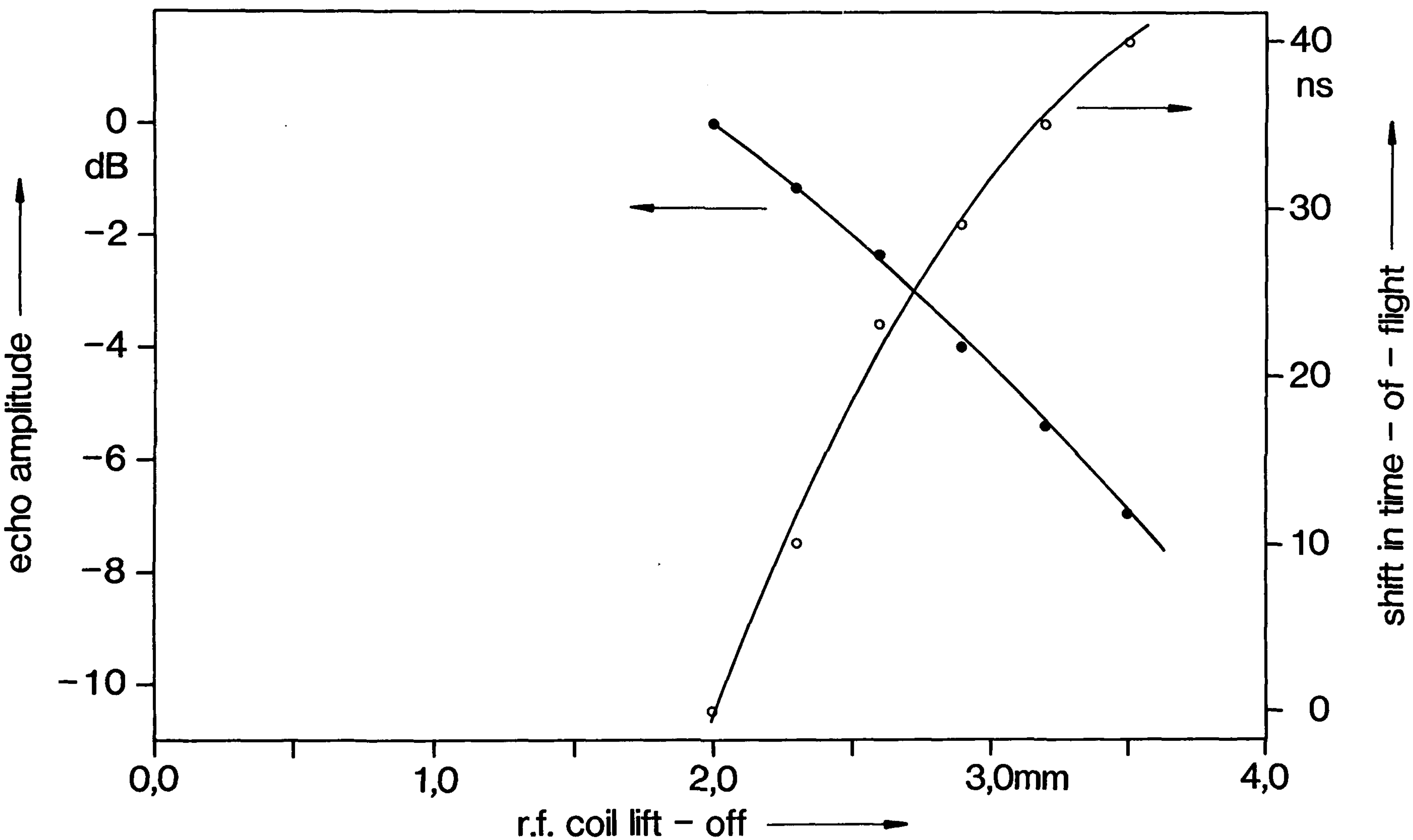
Fig. 6



IzfP

High temperature normal shear wave EMAT on tube segment
(d = 110mm , RT)

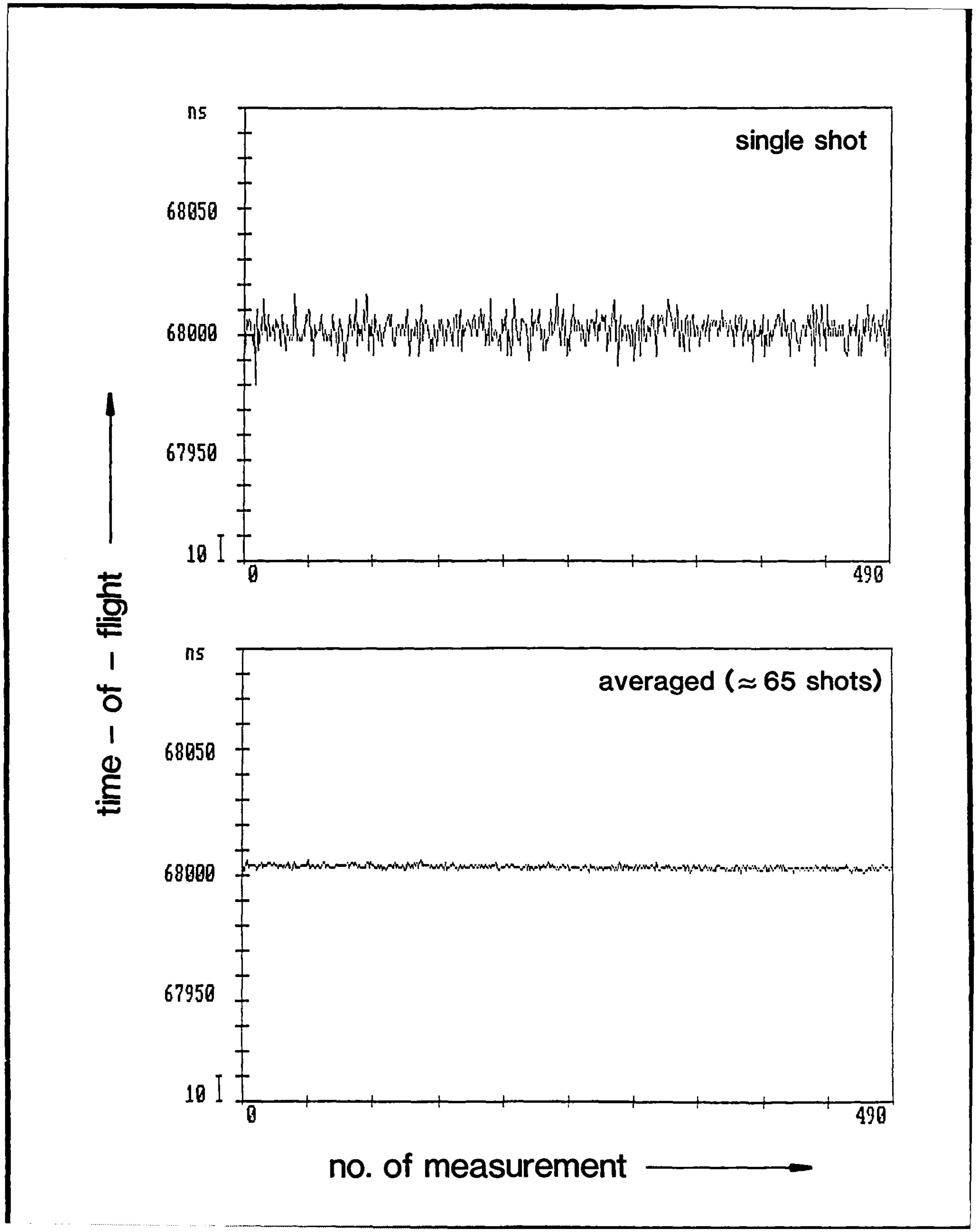
Fig. 7



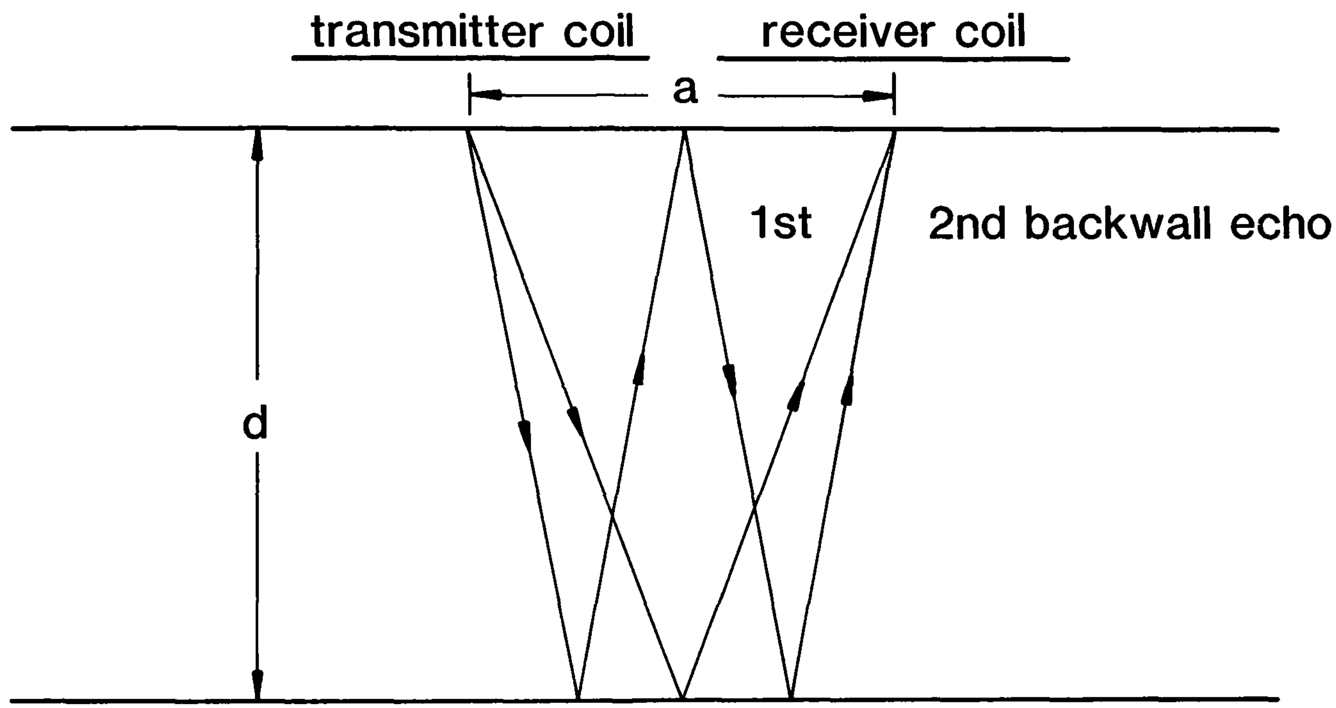
IzfP

High temperature normal shear wave EMAT: lift - off effects

Fig. 8

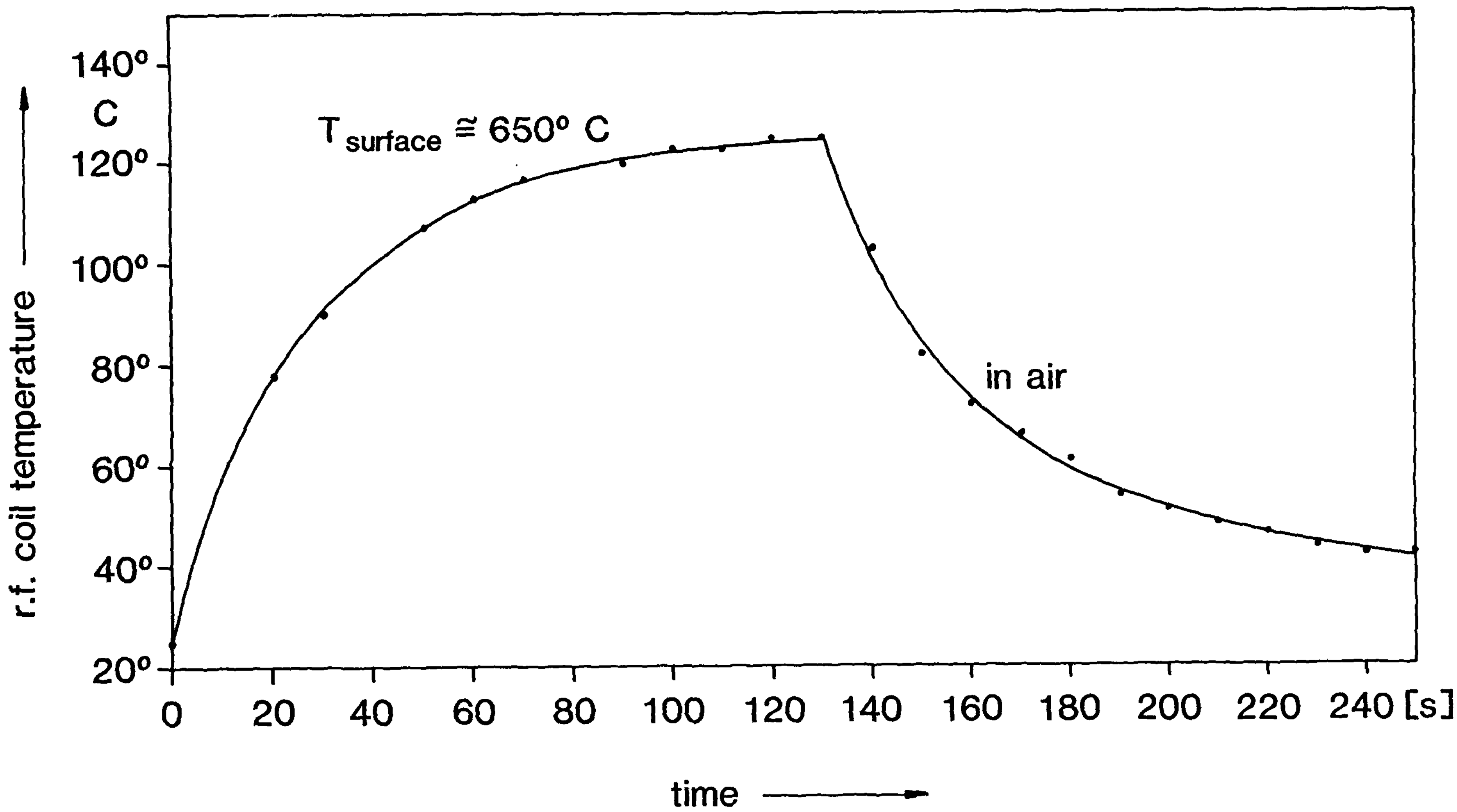


ns
single shot
68050
68000
67950
10
0
490
ns
averaged (≈ 65 shots)
68050
68000
67950
10
0
490
time - of - flight
no. of measurement



Sound path of first and second backwall echo with twin probe

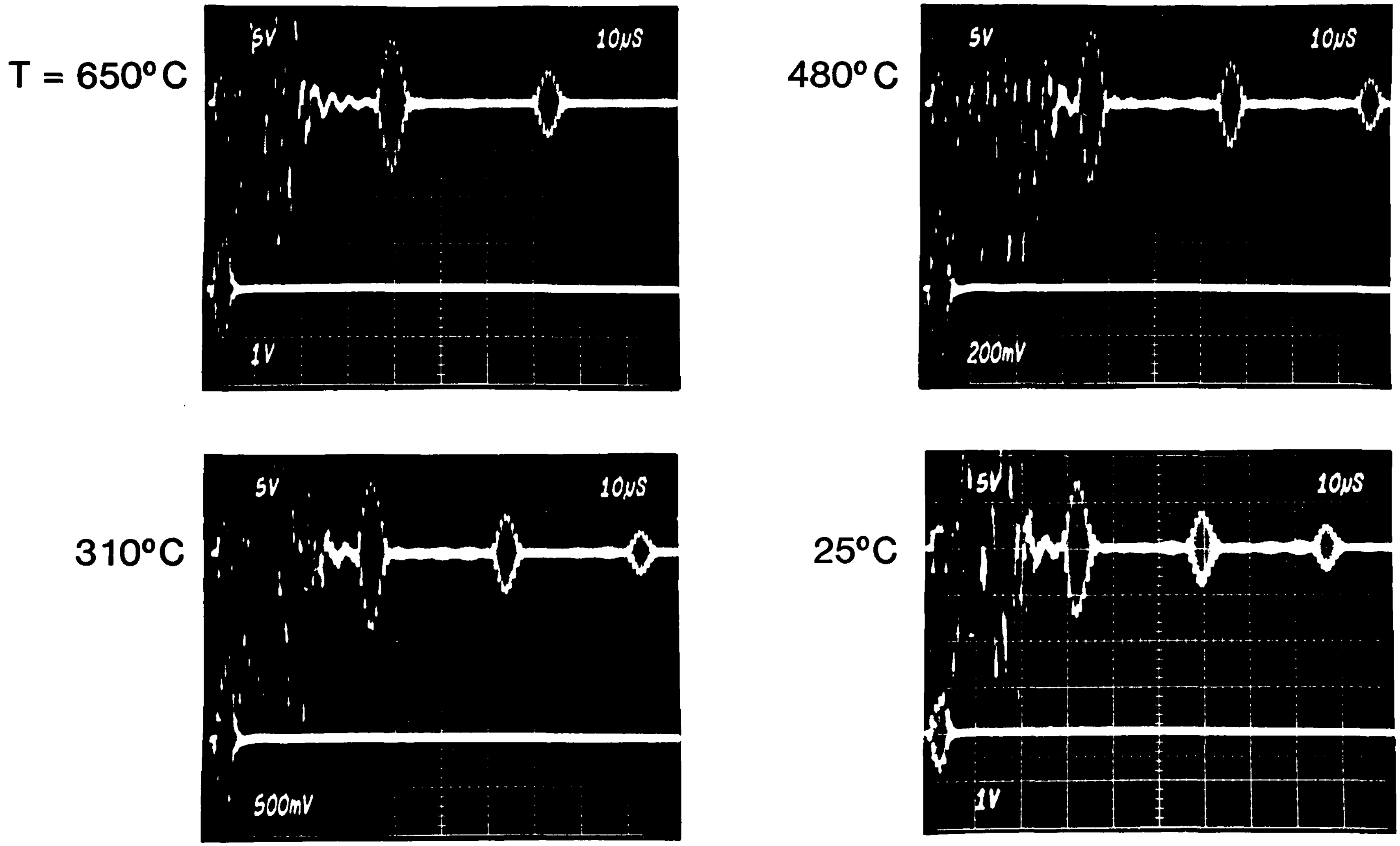
Fig. 10



IzfP

High temperature normal shear wave EMAT :
Heating and cooling cycle

Fig. 11

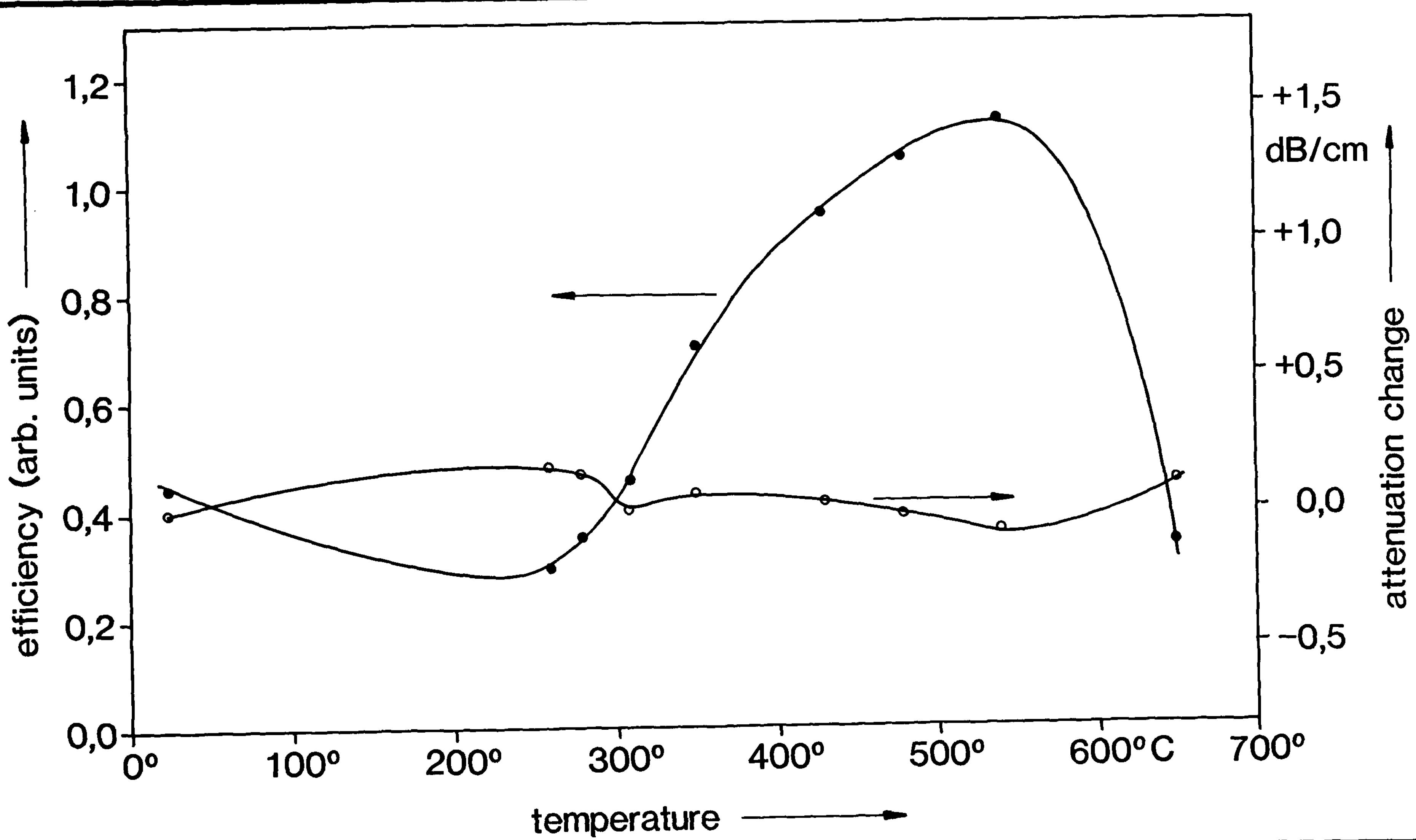


IzfP

High temperature normal shear wave EMAT :

Backwall echoes from a heated steel specimen (d = 45mm)

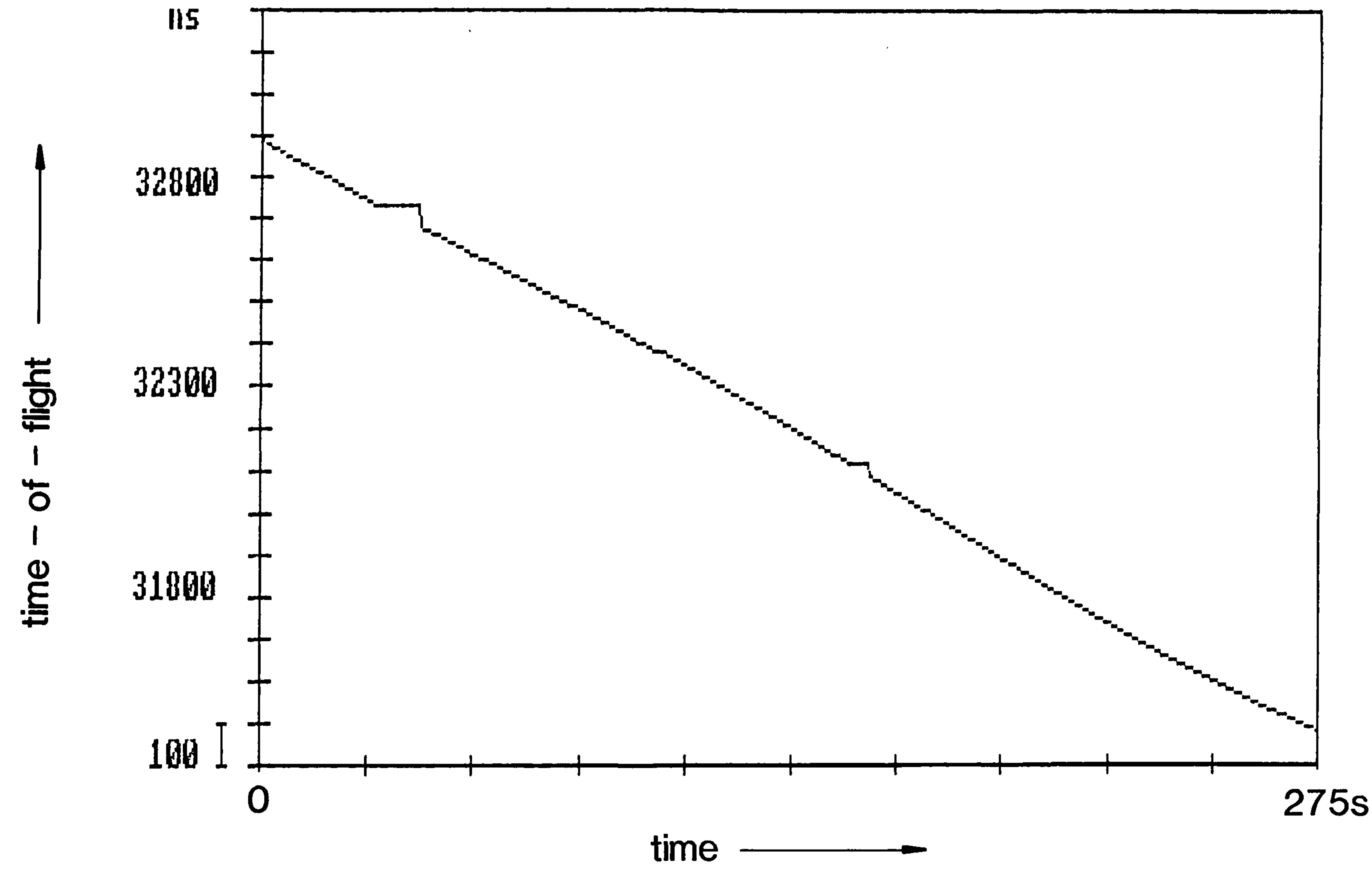
Fig. 12



IzfP

Temperature dependence of EMAT efficiency and shear wave attenuation

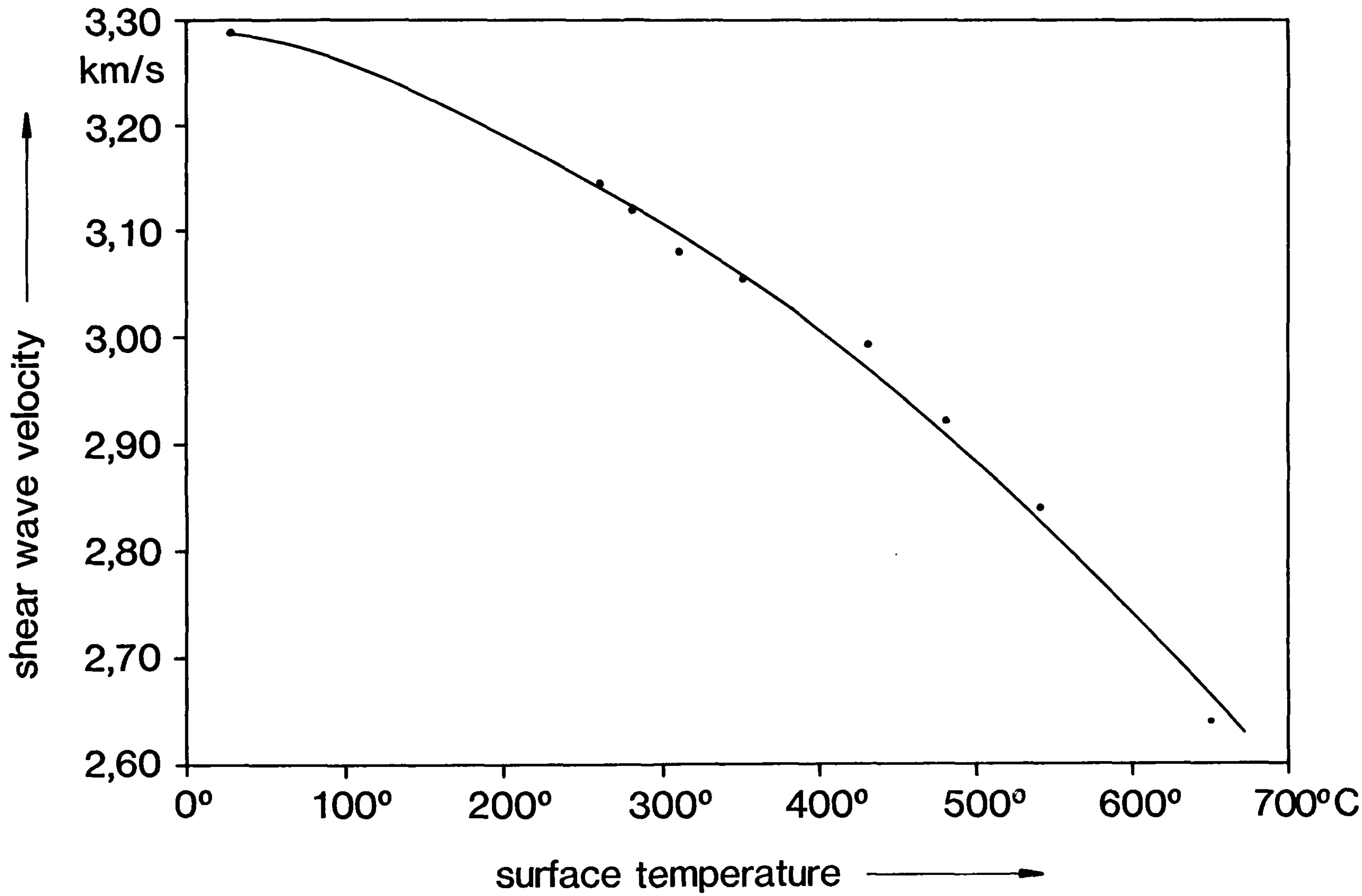
Fig. 13



IzfP

Time – of – flight between 1st and 2nd backwall echo on a hot steel specimen (d ≅ 45mm)

Fig. 14



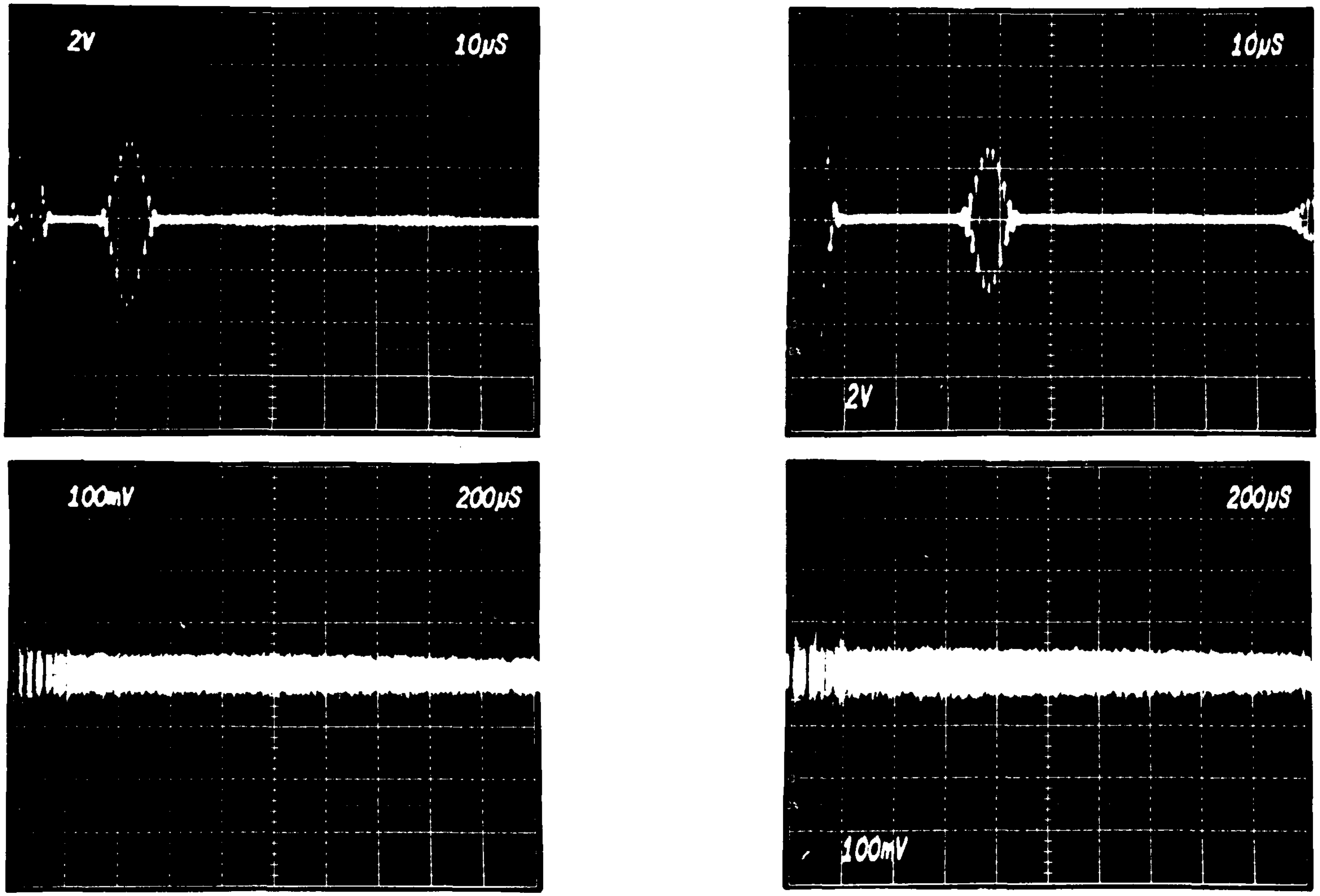
IzfP

Temperature dependence of shear wave velocity

Fig. 15

Receiver 1

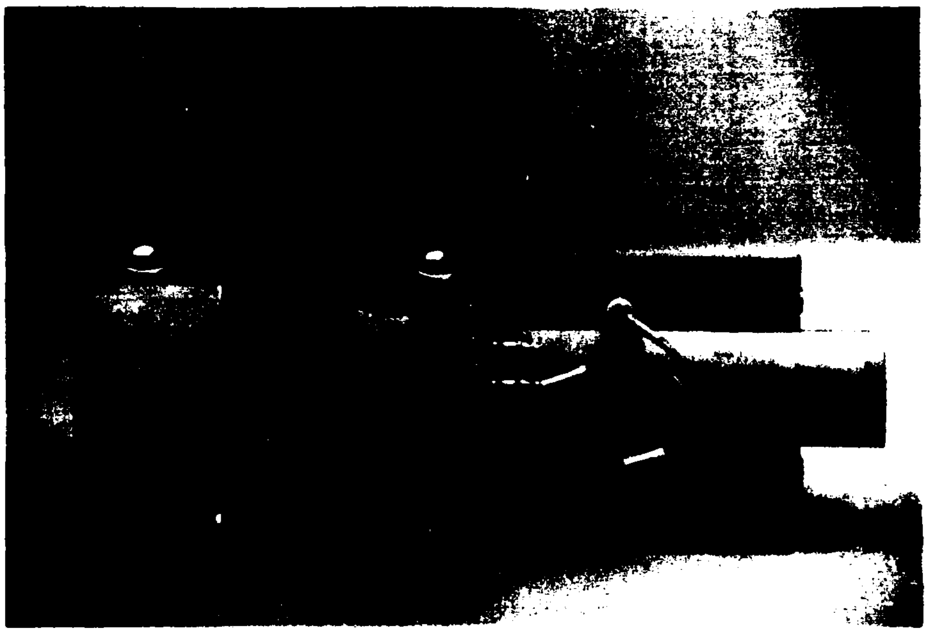
Receiver 2



IzfP

EMUS – transduction of Rayleigh waves on the inner surface of a 120mm gun tube ring section

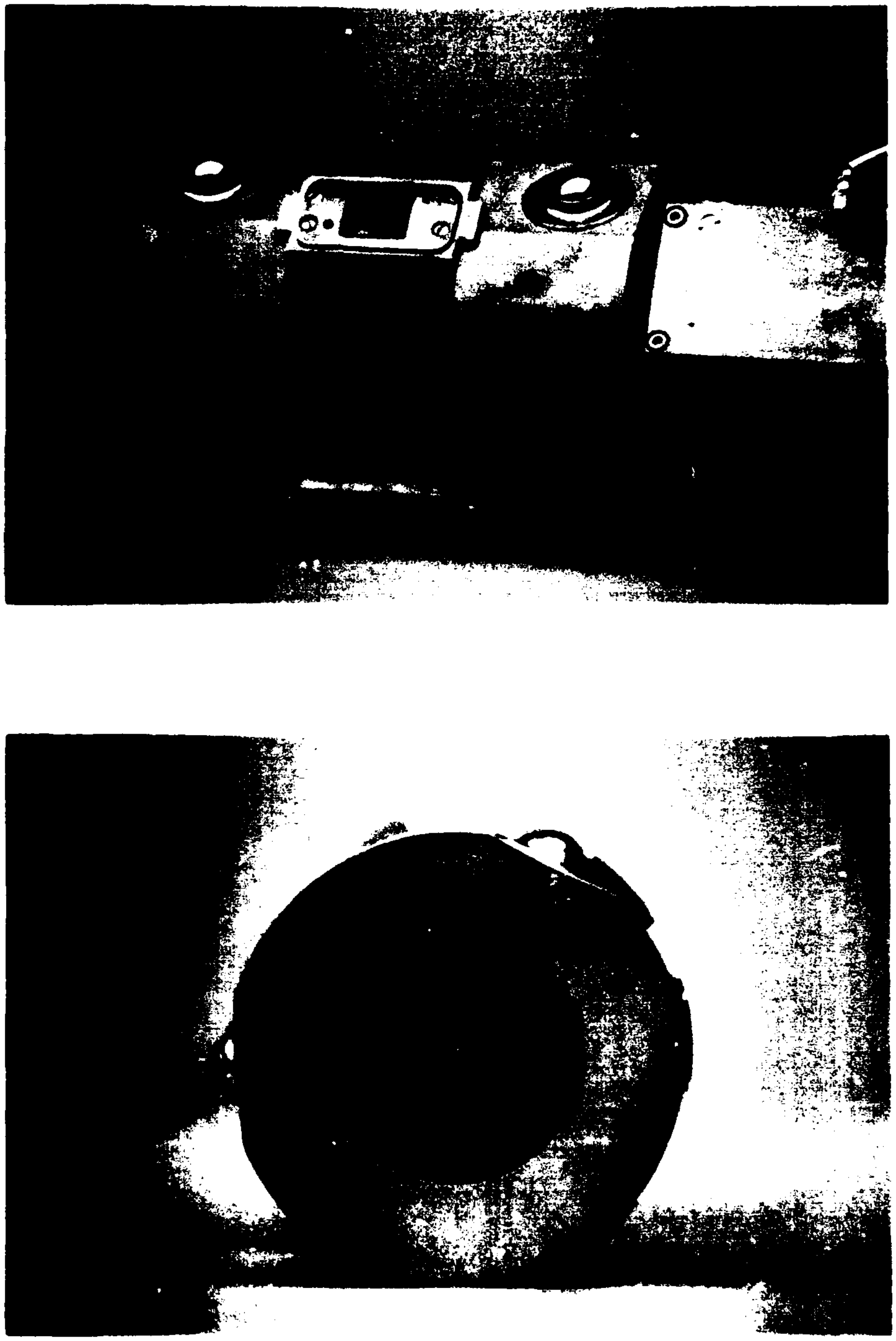
Fig. 16



Rayleigh wave probe head for 120mm gun tube

IzfP

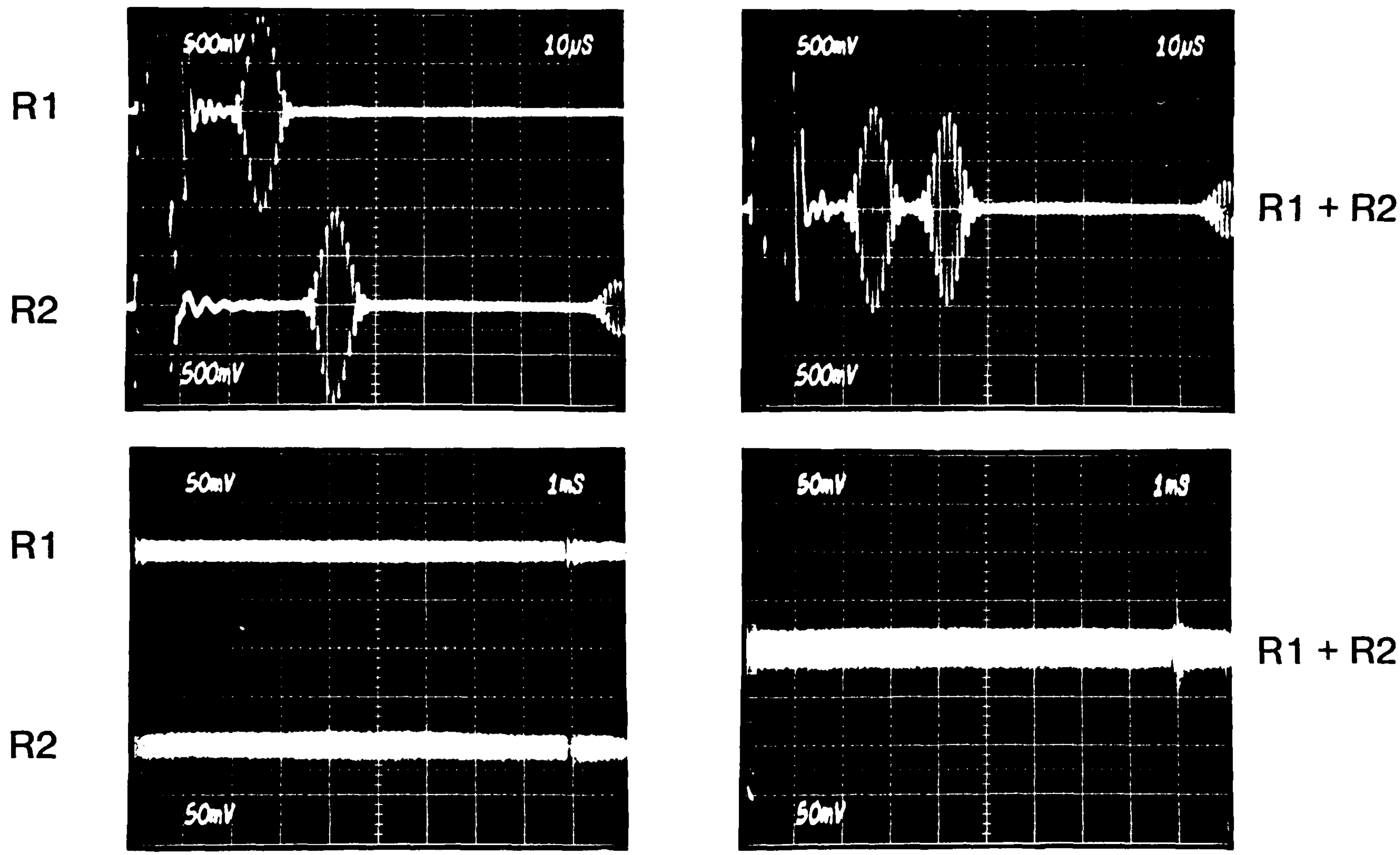
Fig. 17



Rayleigh wave probe head for 120mm gun tube

IzfP

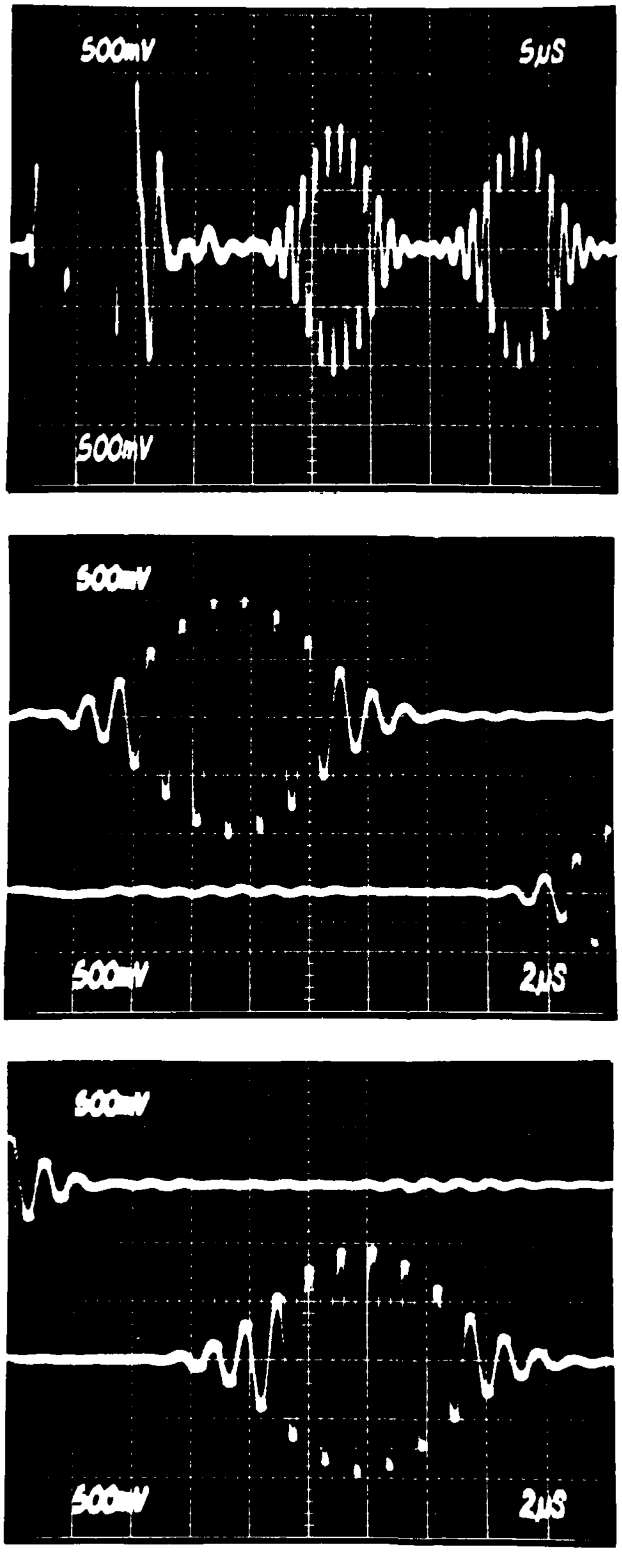
Fig. 18



IzfP

Signals from Rayleigh wave probe head in 120mm gun tube ring section

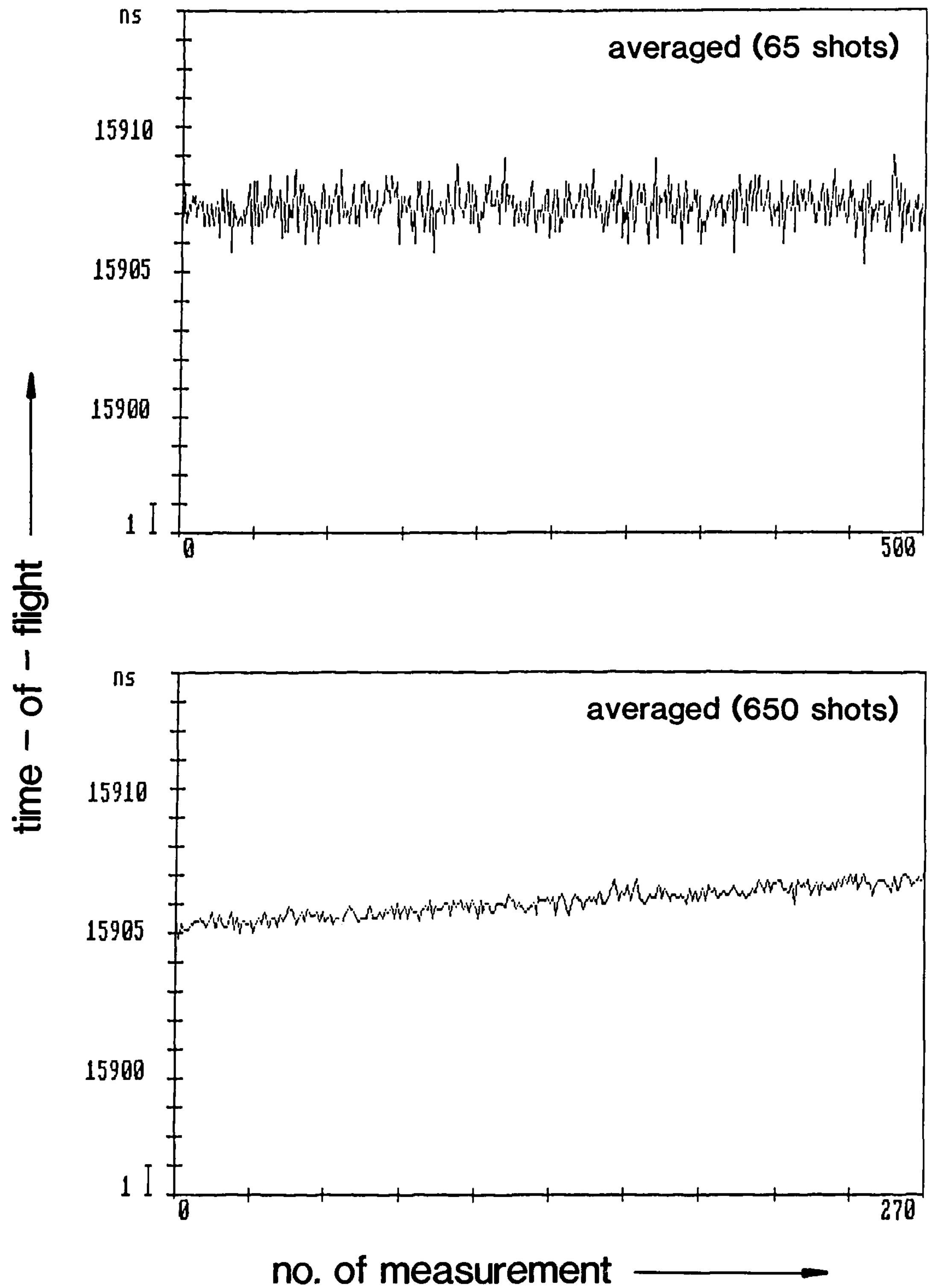
Fig. 19

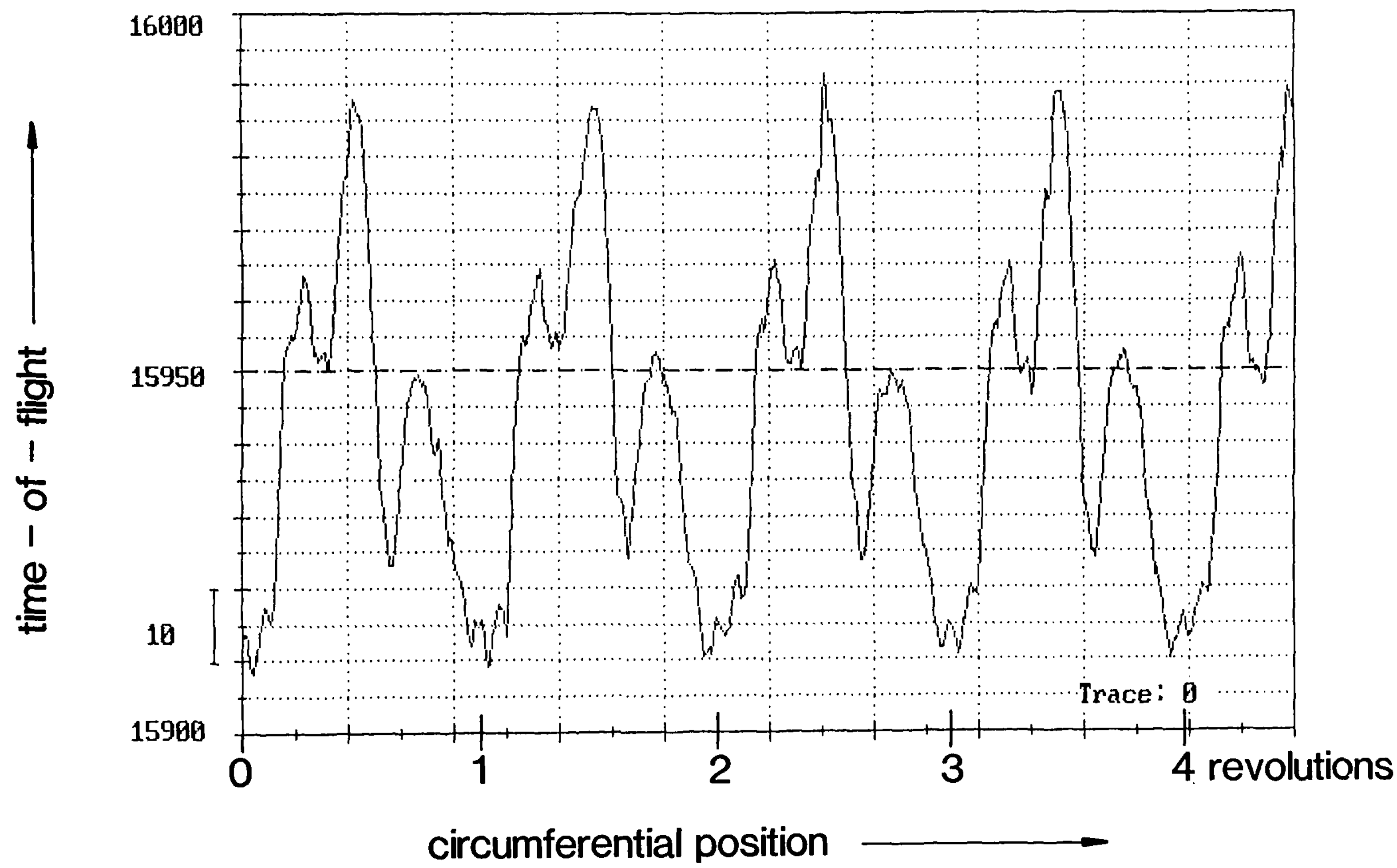


Signals from Rayleigh wave probe head in 120mm gun tube ring section

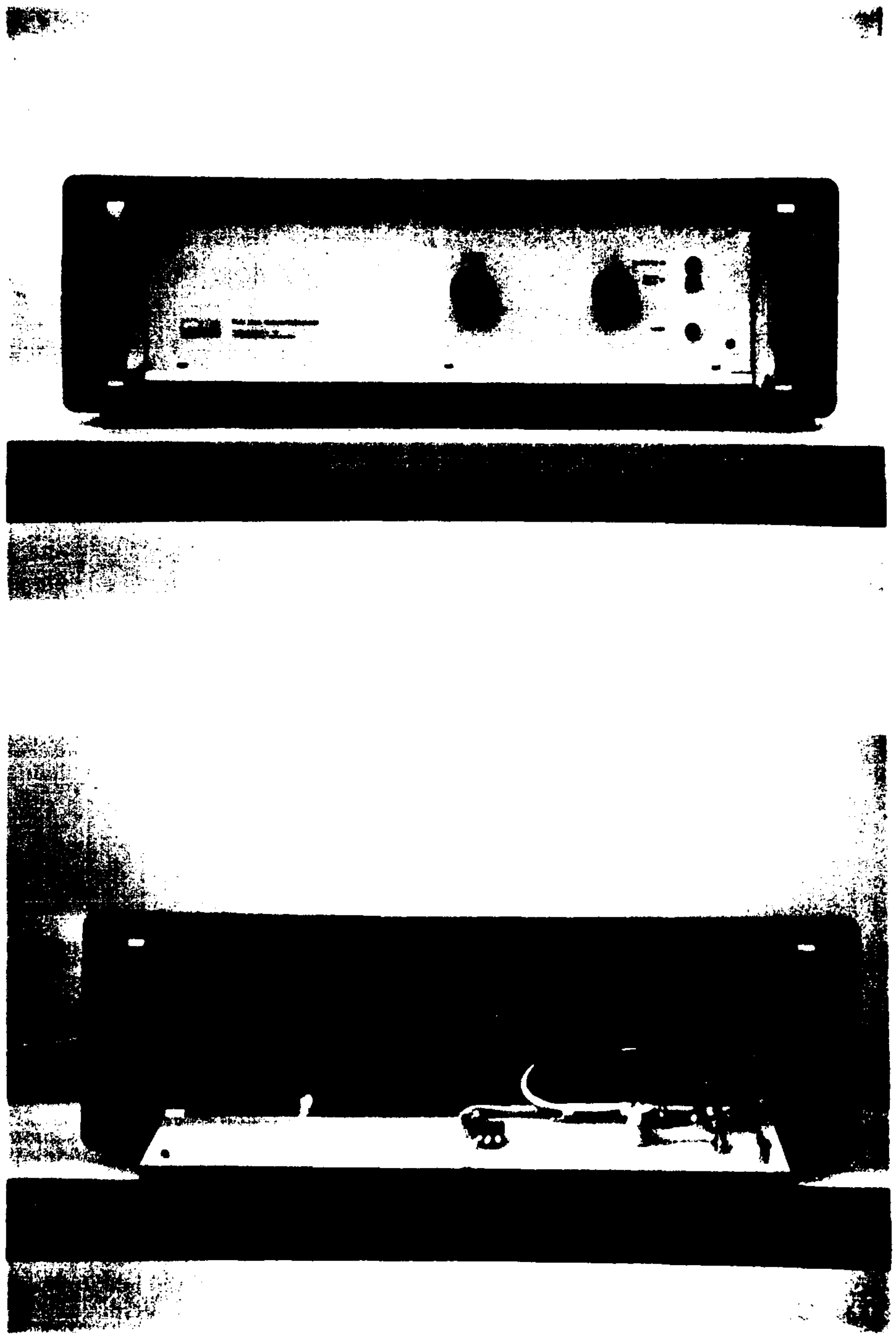
IzfP

Fig. 20


averaged (65 shots)
ns
15910
15905
15900
1
0
500
averaged (650 shots)
ns
15910
15905
15900
1
0
270
time - of - flight
no. of measurement



IzfP | Rayleigh wave time – of – flight measurement on a steel tube ϕ 130 x 5mm | Fig. 22



EMUS transmitter /

receiver instrument G4401

IzfP

Fig. 23